LIMNOLOGICAL SURVEY OF WESTERN LAKE ERIE

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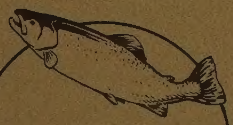

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Explanatory Note

The series embodies results of investigations, usually of restricted scope, intended to aid or direct management or utilization practices and as guides for administrative or legislative action. It is issued in limited quantities for the official use of Federal, State or cooperating agencies and in processed form for economy and to avoid delay in publication.

United States Department of the Interior, Douglas McKay, Secretary,
Fish and Wildlife Service, John L. Farley, Director

LIMNOLOGICAL SURVEY OF WESTERN LAKE ERIE

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With chapters on
The Phytoplankton of Western Lake Erie
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and
The Zooplankton of Western Lake Erie
in collaboration with Wilbur M. Tidd

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LIMNOLOGICAL SURVEY OF WESTERN LAKE ERIE

General Summary

Introduction

For many decades Lake Erie supported a highly productive commercial fishery, but within the past 25 years there has been an alarming decline in production of the more highly prized species, in spite of an increase of fishing intensity. Following the virtual collapse of the cisco fishery in 1925, fishermen, conservation officers, and fisheries biologists alike realized the necessity of a scientific investigation to determine the cause or causes of the decline, and to determine possible remedial measures.

A number of explanations were offered for the decrease of the catch. Fishermen were persistent in their claim that pollution had made parts of the lake unsuitable for fishes. Attention was directed particularly to the western part of the lake because of a number of conditions which make it especially subject to pollution, and because of its importance in the fishery. The conditions which make it especially subject to pollution are: (1) the presence of large industrial communities on the shores of Maumee, Raisin, and Detroit Rivers, which empty into this part of the lake: (2) the extreme shallowness and consequent small volume of water: (3) the presence of two peninsulas and numerous islands which partially separate this area from the rest of the lake, and which tend to prevent free outflow of water. The importance of Western Lake Erie in the fishery arises from the facts that: (1) large numbers of fish are caught there; (2) the area is used as a spawning ground by all of the commercial species except, possibly the blue pike-perch.

The Division of Conservation of the State of Ohio was the first to investigate the degree and extent of pollution with reference to its effect on the fishery of Lake Erie. In the month of August, 1926, and in autumn and winter of 1927, special parts of the lake, particularly along the Ohio shore from Toledo to Cleveland, were studied. In 1928, 1929, and 1930, work was concentrated on the part of the lake west of Point Pelee. The report is based principally on the results obtained in 1929 and 1930.

The general plan of investigation was as follows: It was assumed that the offshore areas of the lake, far from sources of pollution, would be most nearly normal, and that the areas near the rivers would show the maximum effect of pollution. Accordingly the lake was divided arbitrarily into five sections, and parallel studies were made in each section to facilitate comparisons of the results. The offshore area, near the islands, was designated the Island Section, and areas near the mouths of the four rivers studied were designated the Portage River, Maumee Bay, River Raisin, and Detroit River Sections. With minor exceptions the field work was done in the months of April to October, inclusive.

Physical limnology

A general description of Lake Erie and a detailed description of Western Lake Erie, with hydrographic maps and morphometric data, are presented. The literature on fluctuations of lake levels, waves, seiches, tides and currents is reviewed briefly. Studies of currents based on drift bottles show that the surface currents of Western Lake Erie are not constant in direction, but depend upon the direction of the wind.

Because of its extreme shallowness, Western Lake Erie is usually homothermous from top to bottom; thermal stratification appears only occasionally and for short periods. Data on weather are presented. Transparency of the water is low, particularly in spring and autumn.

Chemistry

In the Island Section the oxygen content of the surface water ranged from 7.1 to 13.0 parts per million, and from 83 to 133 per cent of saturation. Almost all of the samples fall between 90 and 99 per cent of saturation. Free carbon dioxide ranged from -5.9 to 3.1 parts per million; methyl orange alkalinity (in terms of calcium carbonate) from 85 to 103 parts per million; pH from 7.7 to 8.5. In general the chemistry of the surface and bottom water was nearly the same. Only one case of nearly total depletion of oxygen in the lower water was found in the three seasons of study. The low oxygen content (8.6 per cent of saturation) was found in the eastern part of the Island Section near the close of a period of temporary thermal stratification, and apparently was restricted to the lower three meters of water.

The average amounts of the different forms of nitrogen in the Island Section were as follows: free ammonia, 0.013; albuminoid ammonia, 0.151; nitrite, 0.005, nitrate 0.10 (part per million). While it is probable that the nitrogen content has been increased by pollution, it is equally probable that the additional demand upon the dissolved oxygen has been small as compared with demands resulting from natural phenomena. From a chemical point of view, polluting materials known to enter the lake apparently have had no harmful effect on the water of the Island Section.

The chloride content of Lake Erie is higher than that of other of the Great Lakes. Chloride has little value as an index of pollution in Lake Erie because of the numerous natural sources of sodium chloride in the drainage basin.

A number of chemical samples were taken in Western Lake Erie near the mouths of four tributary streams (Portage, Maumee, Raisin, and Detroit Rivers), and a few were taken in the rivers themselves. All of the rivers are known to receive sewage from municipalities located on their shores. In relation to its mean discharge, Maumee River receives sewage from the largest population; in this respect River Raisin is second; Portage River third; and Detroit River fourth. Over considerable areas in and near the rivers the bottom was covered by organic debris, which would have a marked effect on the chemistry of the water immediately in contact with it. The following summary applies only to the water one meter or more above the bottom.

Parts of the lake in which there was definite evidence of pollution, as indicated by high albuminoid ammonia, were characterized by low nitrite and nitrate as compared with parts of the lake in which the evidence of pollution was less definite or lacking. This is believed to have resulted from the utilization of nitrite and nitrate by plankton algae, for there was a direct relationship between the abundance of phytoplankton and the intensity of pollution.

Chemical results obtained in Portage River at Port Clinton, and in the lake near the mouth of the river indicate light pollution. The only definite evidence of pollution was in the content of albuminoid ammonia, which was somewhat higher than in the Island Section. In most of the samples the dissolved oxygen content was in excess of 90 per cent of saturation, and in no sample was it less than 77 per cent of saturation. Correspondingly satisfactory results were obtained for free carbon dioxide and pH. It may be concluded that pollution in Portage River has had no harmful chemical effect on the water of Western Lake Erie.

Maumee River near its mouth was heavily polluted as indicated by high free and albuminoid ammonia (0.618 and 0.708 part per million), and by low dissolved oxygen (not exceeding 49 per cent of saturation). Immediately outside the mouth of the river free and albuminoid ammonia were consistently high, and there was definite evidence of the effect of the river water at a distance of 8.5 miles from the mouth. The oxygen content immediately outside the mouth was sometimes low and sometimes high (range: 12 to 112 per cent of saturation), but there were no marked withdrawals of oxygen at a distance of 2.25 miles or more from the mouth of the river. In Maumee Bay the harmful chemical effect of the river water appeared to be restricted to a small area near the mouth of the river.

River Raisin at its mouth was definitely polluted as shown by the high albuminoid ammonia (mean, 0.433 part per million), and by low oxygen content. In one case there was total exhaustion of oxygen. The effect of pollution was evident in the analyses for albuminoid ammonia in the lake at a distance of at least two miles from the mouth of the river, but no marked withdrawals of oxygen definitely referable to pollution were noted at a distance greater than one-half mile, and only then in water recently discharged from the river. Thus, the harmful effect of pollution apparently was restricted to a very small area near the mouth of the river.

There was no definite chemical evidence of pollution in the lake near the mouth of Detroit River, nor in the river near its mouth. In most respects the chemical results were similar to those obtained in the Island Section. On the average there was less decomposing organic matter, as shown by albuminoid ammonia, than in the Island Section. In most of the samples the oxygen content was in excess of 90 per cent of saturation, and in only a few samples was it less than 80 per cent of saturation. Doubtless the nitrogen content of the river water has been increased as a result of pollution, but probably the increase has been too small to have an appreciable effect on the oxygen content of the water. It may be concluded that pollution in Detroit River has had no harmful chemical effect on the water of Western Lake Erie.

The relative positions of the different sections with respect to intensity of pollution as indicated by the chemical data, particularly albuminoid ammonia, were: (1) Maumee Bay; (2) River Raisin: (3) Portage River; (4) Island; (5) Detroit River. In the lower parts of Maumee and Raisin Rivers and sometimes in small areas in the lake near the mouths of these rivers, pollution was sufficiently intense to make the chemical conditions harmful to aquatic organisms which would normally inhabit such areas. In the Portage River, Island and Detroit River Sections there was no evidence of pollution of sufficient intensity to cause harmful chemical conditions.

The results and conclusions reviewed above refer to the period when the lake is free of ice. Determinations of oxygen, carbon dioxide, and pH, made under the ice near the west shore when the period of ice-closure was about three-fourths completed, indicate that chemical conditions there were little, if any, less favorable than those prevailing during the summer.

The available evidence, both direct and indirect, indicates that poisonous substances are not present in the lake in concentrations sufficient to affect aquatic organisms harmfully.

The final conclusion to be drawn from the chemical data is that pollution has had both harmful and helpful effects on chemical conditions in Western Lake Erie. The harmful effect has been the marked reduction in oxygen content of water discharged into the lake from Maumee and Raisin Rivers. The helpful effect has been the addition to the lake water of large quantities of nutritive materials, which probably have made possible a great increase in the abundance of plankton organisms. It is probable that the harmful effect has been offset, largely if not entirely, by the helpful effect.

Phytoplankton

A qualitative study of the quantitative samples showed the presence of 80 genera and 150 species of algae. The list is composed principally of representatives of the Chlorophyceae, Diatomeae, and Myxophyceae. Representatives of other classes are relatively few in number.

The horizontal distribution of the phytoplankton was not uniform in the Island Section. There was little evidence that some stations had consistently high counts and others consistently low count. Indirect evidence from a comparison of seasonal distribution in the two years indicates that the lack of uniformity was not such as to invalidate a determination of average abundance for the area based on samples from several stations.

The vertical distribution was essentially uniform. Differences in abundance at different levels were found, but in general they were not large and were not consistently of the same kind. That is, the greatest abundance may be found near the surface at one time, and near the bottom at another time. In general, samples taken at surface and bottom yielded about the same average count as samples taken at four depths.

Only in the Island Section was sampling continued long enough to trace the seasonal changes in abundance clearly. Nothing is known of the abundance in November, December, January, February, or March; the following summary is based on a study of the remaining months of the year. Diatoms as a group had two maxima, one in spring and another in autumn. In 1929 the spring maximum came in early June; in 1930 in late May. Earlier appearance of the maximum in 1930 probably resulted from earlier warming of the water in that year as compared with 1929. In autumn of 1929 the diatoms reached their greatest abundance in late October, but may have continued to increase for some time after the close of the sampling season. In 1930 only Stephanodiscus was abundant in autumn. It seems probable that the diatoms as a group reached their autumn maximum after the close of the sampling season in early October of this year. Diatoms were more abundant in autumn than in spring of 1929; this may or may not have been the case in 1930. Greens had one maximum and this came in autumn (late September in both years). Blue-greens had one maximum and this coincided with the maximum of greens. Groups other than diatoms, greens, and blue-greens did not make important contributions to the abundance of phytoplankton.

In spring the phytoplankton was composed almost exclusively of diatoms. In summer all groups were rare, although the diatoms were definitely dominant in 1929. The autumn maximum was composed of large numbers of all three groups.

For comparable periods of time, the two years agreed closely with respect to (1) average abundance of phytoplankton groups, (2) times of changes in abundance, and (3) degree and direction of change. For the period late May - early October, the two-year averages, stated in thousands of units per liter, were as follows: diatoms, 90; greens 38; and blue-greens 58. The highest average counts in period of two weeks (not necessarily the same period for each group) were: diatoms, 261; greesn, 128; and blue-greens, 203. The lowest were: diatoms, 14; green 0.5; and blue-greens, 0.5. The highest average count of all groups combined for a single period was 544, and the lowest 33.

The genera of diatoms and blue-greens which made important contributions to the plaknton were almost the same in both years, but there were about twice as many important genera of greens in 1930 as in 1929.

The Island Section of Western Lake Erie is richer in plankton than Lake Erie east of that area, and richer than Lake St. Clair. Comparisons with Lake Mendota, a eutrophic lake, and Green Lake, an oligotrophic lake, on the basis of the dry weight of organic matter in the centrifuge plankton in autumn (and other considerations), show that Western Lake Erie stands between the two in richness. It probably stands nearer to Lake Mendota than to Green Lake. Since these two lakes are fairly typical of their classes, and since eutrophic lakes are generally rich and oliogotrophic lakes generally poor, the Island Section of Western Lake Erie might be described as "moderately rich" in plankton.

Large and highly consistent inequalities in horizontal distribution exist in Western Lake Erie as a whole. For the months of July, August, and September of 1930, the average abundance per unit volume of water in the Detroit River Section was 1/4 of that is the Island Section; 1/11 of that in the Portage River Section; 1/16 of that in the River Raisin Section; and 1/26 of that in the Maumee Bay Section. The data do not permit such a definite statement of relative abundance for 1929. As far as comparisons can be made, they indicate that the relative positions of the sections were the same in both years (with one minor exception) but that differences in abundance were not as marked as in 1930. The algae were distinctly more abundant in Maumee Bay and River Raisin Sections in 1930 than in 1929. Qualitatively, the sections having the most abundant plankton were characterized by the dominance of blue-greens over greens and diatoms.

The most probable explanation of the differences in abundance between sections is as follows. The sections which are now especially abundant in plankton (Maumee Bay, River Raisin, Portage River Sections) were abundant in plankton under natural conditions. Shallowness of the water is believed to have been the principal contributing factor in this richness, with the added factor, in the case of the Portage River Section, of the lacustrine character of the lower river. Superimposed upon this natural richness is the richness caused by the nutritive salts derived from domestic sewage. Detroit River Section is poor in plankton because the source of the river, Lake St. Clair, is poor in plankton, and not because of the destructive effect of poisonous chemicals derived from industrial wastes. There is little or no local increase of abundance resulting from domestic pollution in this section. The natural abundance of plankton in the Island Section has been increased as a result of pollution, by the eastward drift of organisms produced near the rivers, and by the use of the excess of nutritive salts. The relative positions of the different sections of the lake with respect to abundance of phytoplankton was the same as with respect to intensity of pollution as indicated by the content of albuminoid ammonia.

Zooplankton

The crustacea were not uniformly distributed in the Island Section, but there is no evidence that they were consistently abundant at certain stations and consistently rare at others. Comparisons of seasonal distribution of individual genera in 1929 and 1930 indicate that the lack of uniformity was not such as to invalidate a determination of average abundance in the section based on samples from several stations.

Vertical distribution was studied only during the hours of daylight, so that nothing is known regarding diurnal migrations. In the daytime the adult crustacea were usually rare at the surface and near the bottom, and were most abundant at some intermediate depth. Nauplii and rotifers appeared not to avoid the water near the surface, but were commonly concentrated at more than one level. There were numerous exceptions to any general rule regarding vertical distribution of the zooplankton organisms.

Only in the Island Section was sampling continued over a sufficiently long period to show seasonal distribution clearly. Nothing is known definitely regarding abundance in the months of December, January, February, and March, but there are reasons for believing that the crustacea are rare during that period. During the remaining months the adult crustacea were rare in spring and autumn, and were most abundant in summer. In 1930 copepod nauplii were most abundant in late spring, and this probably was true in 1929 also.

The four most prominent general of crustacea were Cyclops, Diaptomus, Daphnia, and Diaphanosoma. For the period late May - early October for the years 1929 and 1930, the mean counts per liter in the Island Section were as follows: Cyclops, 10; Diaptomus, 6; Daphnia, 4: Diaphanosoma, 1. The corresponding mean for the nauplii was 16 per liter. Comparisons of these figures with corresponding figures from a typical eutrophic lake and a typical oligotrophic lake show that the Island Section holds an intermediate position with respect to abundance of crustacea. Since eutrophic lakes are characteristically rich in plankton and oligotrophic lakes are poor, Western Lake Erie in the Island Section may be described as "moderately rich" in plankton crustacea.

Large and highly consistent inequalities in horizontal distribution exist in Western Lake Erie as a whole. For the months of July, August, and September of 1930, the mean number of crustacea in the Detroit River Section was 1/13 of that in the Island Section; 1/17 of that in the River Raisin Section; and 1/20 of that in the Maumee Bay Section. Differences of similar magnitude were found for about the same period of time in 1929. These differences in abundance of the plankton crustacea are believed to be dependent upon the amount of food available to them, for in 1930, and probably in 1929 also, the different sections just mentioned held the same positions with respect to abundance of phytoplankton as they did with respect to plankton crustacea. That is, the Maumee Bay Section was first in abundance of both kinds of plankton organisms, the River Raisin was second, the Island Section third and the Detroit River Section fourth. The Portage River Section is not included in the list because it is represented by less adequate data.

It is believed that the observed differences in abundance in different sections are in part the result of natural conditions, and in part the result of pollution. In all probability, the increase of phytoplankton and organic detritus resulting from pollution has made possible an increase of the crustacea.

Bottom Organisms

The criteria of pollution employed were as follows: A mud bottom having less than 100 tubificid worms and more than 100 Hexagenia nymphs per square meter was considered to be free from pollution; a larger number of tubificids and smaller number of Hexagenia was regarded as evidence of pollution. Three degrees of pollution were recognized, based on the number of tubificids per aquare meter, as follows: light pollution, 100-999; moderate pollution, 1,000-5,000; heavy pollution, more than 5,000. On other than mud bottom, only the tubificids were used as a criterion of pollution.

In the Island Section quantitative samples were taken only on mud bottom. Nymphs of the burrowing mayfly, Hexagenia, were more abundant than all other organisms combined. In 1929 the average number of Hexagenia for seven stations was 283 per square meter, which was 65 per cent to the total number of organisms. In 1930 the average number for five stations was 510 per square meter, which was 87 percent of the total. Considering only the four stations sampled in both years, Hexagenia was about one and one-half times as abundant in 1930 as in 1929. In both years most of the sampling was done after the period of emergence of the insects. Very probably sampling throughout the year would have shown much higher counts of Hexagenia. Tubificid worms were rare in both years. Areas with mud bottom in the Island Section may be regarded as free from pollution by organic debris. Hauls of the bottom sled in the shallower areas having hard bottom showed that these also were not polluted.

The average dry weight of Hexagenia nymphs for the two years was 43.2 kilograms per hectare (38.5 pounds per acre). This figure is close to that for all organisms in a similar zone of Lake Mendota; it is below that of Lake Wawasee, but above that of three other North American lakes. Thus, the Island Section compares favorably with inland lakes with respect to the weight of bottom organisms per unit of area.

There was no evidence of pollution of the bottom in the Portage River Section near the mouth of the river. Definite evidence of pollution was found near the mouths of the rivers in the Maumee Bay, River Raisin, and Detroit River Sections. The estimated extent of the zones of heavy, moderate, and light pollution for each section is shown in Figure 23, and their areas are given in Table 100. The areas of the zones of pollution were as follows: Heavy pollution, 25.2 square kilometers (9.7 square miles; moderate pollution, 46.3 square kilometers (17.9 square miles); light pollution, 191.4 square kilometers (73.9 square miles). The total area in the three zones of pollution was 262.9 square kilometers (101.5 square miles), or 7.7 per cent of the water area of Western Lake Erie exclusive of Sandusky Bay. Of the total area in the three zones of pollution, 72.8 per cent fell within the zone of light pollution, and an unknown but considerable part of this zone was free of organic debris.

Effects of Pollution on the Fishery

The extent and degree of pollution in Western Lake Erie has been determined with some degree of exactness, but interpretation of the facts in terms of the effects on the fishery must be based largely on conjecture. Some of the effects of pollution are obviously harmful to fishes and hence to the fishery, while others are clearly advantageous. However, there are no standards by which they can be measured and compared quantitatively to determine the residual effect on the fishery. No attempt will be made here to enter into a detailed discussion of the problem. Briefly stated, the conclusions reached are as follows. Conditions in the lower parts of Maumee and Raisin Rivers, and in small areas of the lake near their mouths, have been made unfavorable or prohibitive to all except the most tolerant fishes by reason of the low content of oxygen and high content of free carbon dioxide. In addition, considerable areas of the bottom near Maumee, Raisin and Detroit Rivers have been rendered unfit for spawning purposes by the deposition of organic debris, but it should be recognized that a large part of the polluted area probably never was suitable for spawning because of the deposition of silt. These harmful results of pollution have been offset, partially or wholly, by the increase in plankton organisms which are used as food by all young fishes and the adults of certain species. In view of the tendency of the harmful and helpful effects to balance each other, it seems highly improbable that pollution in the western part of the lake has been the controlling factor in the depletion of the fishery of Lake Erie.

GENERAL INTRODUCTION

Need for Investigation

The fishes of the Great Lakes constitute a natural resource of immense commercial and recreational value. Conservation of this resource has become a major problem confronting various governmental agencies in Canada and the United States.

For a period of 50 years the average annual production of commercial fish in the Great Lakes was 100,000,000 pounds, and in many years Lake Erie accounted for roughly one half of the total catch. As early as the decade prior to 1870 there was definite evidence of a decline in the abundance of fish, but production has been maintained at a high level by increasing the intensity of fishing effort, and by seeking the less desirable species.

Concern has been felt particularly for the fishery of Lake Erie because of the great decline in the highly prized whitefish and cisco. Milner (1874) reported the presence of a lucrative whitefish fishery in Detroit River, but in the last decade of the century, this fishery was abandoned as a commercial venture and there was evidence of depletion in Lake Erie (Rathbun and Wakeham, 1897). With the decrease in the supply of whitefish, the cisco was sought with increasing intensity, and this species held first place in production in Lake Erie until it suddenly became almost commercially extinct in 1925 (Van Oosten, 1930). Certain other species have shown unmistakable evidences of depletion. For more detailed information on the fishery, the reader may refer to Koelz (1926), U. S. Tariff Commission (1927), Higgins (1928a and 1929), Van Oosten (1929a), and Fiedler (1931).

Following the virtual collapse of the cisco fishery, fishermen, conservation officers, and fisheries biologists alike realized the necessity of a scientific investigation to determine the cause or causes of the decline of the fishery, and to determine possible remedial measures. Since depletion was first noted, two possible explanations have been especially prominent in discussion of the problem: (1) excessive fishing and destructive methods of fishing, and (2) pollution of the tributaries and of the lake by domestic sewage and industrial wastes. Fishermen, particularly, were persistent in their claim that pollution had made parts of the lake unsuitable for fishes. It was held that the deposition of sludge had rendered large areas unfit for spawning; that there was not sufficient oxygen in the water; and that the quality and quantity of food had declined. Further, many claimed that poisonous substances had caused the death of large numbers of fish. Attention was directed to the western part of the lake because of a number of conditions which make it especially subject to pollution, and because of its importance in the fishery.

The conditions which make Western Lake Erie especially subject to pollution are: (1) the presence of large industrial communities on the shores of Maumee, Raisin, and Detroit Rivers, which empty into this part of the lake; (2) the extreme shallowness and consequent small volume of water;(3) the presence of two peninsulas and numerous islands which partially separate this area from the rest of the lake and which tend to prevent free outflow of the water. The importance of Western Lake Erie in the fishery arises from the facts that (1) large numbers of fish are caught there, (2) the area is used as a spawning ground by all of the commercial species except, possibly, the blue pike-perch. Because of the supposed intensity of pollution here and the unusual opportunity for it to be harmful to fishes, particularly during their early stages of development, it was generally believed that investigation should center in the western part of the lake. It was believed,too, that, if it could be shown that pollution was not the controlling factor in the depletion of the fishery here, pollution could be ruled out as a controlling factor elsewhere in the Great Lakes.

The present report includes the results of a series of limnological investigations begun by the Conservation Division of the State of Ohio in 1926, and continued in parts of the years 1927, 1928, 1929, and 1930. A history of these investigations will be presented in later pages.

Previous Investigations in Lake Erie

Prior to 1926 no comprehensive survey of the physical, chemical, and biological conditions in Lake Erie had been made. This should not be taken to mean that nothing was known of such conditions. On the contrary there had been accumulated, over a period of years, much information concerning morphometry, temperatures, currents, chemical constituents of the water, the kinds and general abundance of the plants and animals, and many related subjects. The literature covering the flora and fauna of the lake was particularly extensive as a result of the activities of investigators at the Lake Laboratory (later the Franz Theodore Stone Laboratory) of Ohio State University (see bibliographies compiled by Miller (1933) and Osborn (1930)). In addition there had been some studies of the abundance of plankton,and numerous sanitary surveys to determine the suitability of the water for domestic consumption.

The nearest approach to a limnological survey such as the one reported here, was the investigation begun in 1898 under the auspices of the United States Commission of Fish and Fisheries. In that year Professor Jacob E. Reighard was placed in charge of a staff of workers and a laboratory at Put-in-Bay. During the four years that the laboratory was maintained, much was learned of the organisms of the lake, but the original plans for a unified program of research were not realized. Following the abandonment of the laboratory in 1902, limnological investigations of the survey type were not taken up again until 1926.

Thus, at the time this investigation was begun, the plants and animals of the lake were quite well known from a qualitative point of view; quantitatively the situation was quite different. Almost nothing was known of the actual or relative abundance of plankton, or of its vertical, horizontal and seasonal distribution. Still less was known of the abundance and distribution of the bottom organisms. The chemistry of the water with respect to dissolved gases, particularly near sources of pollution, had not been studied. In short there was a general lack of definite information regarding the suitability of the lake for fishes. This report supplies some information by which the suitability of the western part of the lake may be judged.

In 1928 a number of cooperating agencies began a limnological investigation of Lake Erie east of Long Point, under the immediate direction of Dr. C. J. Fish. In 1929 the program was extended to include all of the lake east of Point Pelee, that is, east of Western Lake Erie. The results of the first year of study have been published (Fish, 1929), and will be discussed in some detail in the appropriate chapters of this report. In view of the fact that the survey was made with special reference to the cause of the decline of the fishery, it may be well to point out here that nothing was found in the physical, chemical, and biological conditions to explain the decline.

History of the Present Investigation

It seems advisable to present an historical account of the present investigation, which was begun in 1926 and completed in 1930. In a sense it was a series of investigations, rather than one investigation, for, although the ultimate objective remained the same, the personnel of the scientific staff, the base of operations, and the methods of procedure changed from time to time. In the interests of simplicity of presentation, it has been found convenient to include other than historical materials in the account which follows.

Season of 1926

In the summer of 1926, at the urgent request of fishermen and others interested in commercial and game fishing in Lake Erie, the Ohio Division of Fish and Game (now the Division of Conservation) undertook a study of the extent and degree of pollution in the lake, with special reference to the effect of pollution upon the fishes. Dr. Raymond C. Osburn, Head of the Department of Zoology and Entomology of Ohio State University, was asked to direct the work, which he generously agreed to do without remuneration. The personnel of the scientific staff, and a note as to the field of investigation of each, follows:

R. C. Osburn, Ohio State University.	(Bottom fauna).
R. V. Bangham, College of Wooster.	(Zooplankton)
L. H. Tiffany, Ohio State University.	(Phytoplankton).
H. R. Eggleston, Marietta College.	(Bacteriology).
B. P. Hanan, Rocky River High School.	(Chemistry).

Dr. Osburn, as Director of the Franz Theodore Stone Laboratory of Ohio State University at Put-in-Bay, offered the facilities of the laboratory for the use of the staff. The steam tug, *O. H. Perry*, and the motor cruiser, *Veto*, of the State of Ohio's fleet, were available for work on the lake. Eleven days in the month of August were devoted to field work. A total of 48 stations were visited. These were established at points in the open lake and near sources of pollution so that some idea could be gained of the extent of pollution. Observations were made of temperature, dissolved oxygen and hydrogen ion concentration, bottom organisms, bacteria, phytoplankton, and zooplankton. The study of bottom organisms and plankton was not quantitative, except in a general way.

The results of this preliminary study have been published in mimeographed form (Osburn, 1926 and 1926a), and will not be given in detail here, but will be reviewed in the appropriate chapters. However it may be well to present a rather general statement of the results to form a background for the more detailed data of later years which will be given in the body of the report.

Numerous localities were noted where the dissolved oxygen was considered reduced, but none where the oxygen deficiency would, of itself, prevent fishes from existing. The lowest observed was 2.6 cubic centimeters per liter (3.7 parts per million). Oxygen was found in sufficient quantity almost everywhere, even over bottoms that were foul with decaying matter. In the deeper water of the open lake, even when not far off shore from sources of pollution, the oxygen content of the water was never dangerously low. There was an abundance of oxygen near the mouth of Detroit River; in one sample the water was completely saturated. No acid water was encountered; the hydrogen ion concentration ranged from 7.0 to 8.6.

Sulphur bacteria were found abundantly in the most polluted areas, and the colon bacillus, *B. coli*, was widely distributed. Enclosed areas and regions near large cities showed large numbers of sewage bacteria, but the number diminished rapidly as the distance from sources of pollution increased. Pollution of shore waters and enclosed bays rendered these areas unsafe for recreational purposes and unsatisfactory as a source of municipal water supply.

It was noted that plankton was scanty near the mouth of Detroit River, but very abundant in certain areas where there was definite evidence of pollution.

Considerable areas of the bottom near the large cities, particularly in the harbors and channels leading from them, were covered with organic debris, which made the area unsuitable for spawning. In some cases, as in Maumee Bay, the steamship channel tended to retain the suspended organic matter and permit it to be carried much farther from the river than it otherwise would have been carried. The principal organisms present on the polluted bottom were oligochaete worms.

This brief preliminary survey brought out clearly that the lake was heavily polluted near the large cities, and that the intensity of pollution diminished rapidly with increased distance from the sources. Aside from the reduction of space available to spawning fishes, pollution appeared not to be sufficiently intense or widespread to constitute a serious menace to fish life in the lake.

Season of 1927

In 1927 active direction of field work was taken over by Mr. E. L. Wickliff. However, Dr. R. C. Osburn retained close connection with the investigation in an advisory capacity. A field station was established at Sandusky, Ohio, and work was carried out in the autumn and winter of 1927. In addition to Mr. Wickliff, the scientific staff consisted of W. M. Tidd, biologist, and M. K. Young, chemist, both of Ohio State University. During this season attention was given principally to the fishes themselves, rather than to environmental factors. Study was made of the food and parasites of several species taken in Sandusky Bay and in the lake proper. Data on length and weight, and scales from a considerable number of fish were taken. These results will be presented in a separate report. Some environmental studies were made, but principally in areas outside of Western Lake Erie. For that reason the results will not be given here.

Season of 1928

In 1928 the base of operations was shifted again to Put-in-Bay, and a laboratory was established in the hatchery maintained by the State of Ohio. The personnel of the scientific staff was the same as in the preceding year. In this season, for the first time, parallel studies of the fishes and their environment were made. The principal immediate objective was to correlate the distribution and abundance of the larval, post-larval, and adult stages of the fishes with such environmental factors as temperature, currents, dissolved gases, plankton, and bottom organisms. Of necessity the limnological observations were made subordinate to those on the fishes.

The motor boat Investigator was outfitted especially for use of the scientific staff. Work was concentrated in the area west of Point Pelee, although some observations were made in the central basin of the lake. A large number of stations were established and these were visited at fairly regular intervals during the season, in order to determine seasonal changes as far as possible.

The results of this investigation, as far as they concern the fishes, will be presented in another report. A large part of the physical, chemical, and biological data are incorporated in the appropriate chapters of this report.

Season of 1929

In making plans for the program of 1929, it was decided to continue the parallel studies of 1928, but to facilitate the work, the staff was divided into two groups. One group included those working in fisheries biology; the other, those working in limnology. At the request of the Ohio Division of Conservation, the United State Bureau of Fisheries assigned the writer to the task of directing the field work in limnology, under the supervision of Dr. John Van Oosten, In Charge Great Lakes Fishery Investigations. The other members of the staff, listed below, were employed by the Ohio Division of Conservation, and the costs of equipment and maintenance of the survey also were borne by that agency. This plan of administration was continued in 1930.

The use of two motor boats, *Investigator* and *Veto*, made possible independent but parallel studies of the two phases of the problem in hand. The account which follows concerns only the limnological part of the survey.

The personnel of the staff is given below, together with an indication of the institution with which each was connected at the time, and of the duties or field of investigation on the survey:

E. L. Wickliff, Chief, Bureau of Scientific Research, Ohio Division of Conservation. (Director of the Survey).
Stillman Wright, United States Bureau of Fisheries. (In charge of limnological investigations).
Wilbur M. Tidd, Ohio State University. (Zooplankton)
L. H. Tiffany, Ohio State University. (Phytoplankton).
William C. Beaver, Wittenberg College. (Bacteriology)
Elbert B. Ruth, University of Wisconsin. (Bottom fauna).
Doris Ann Wright, University of Wisconsin (Plankton).
C. J. Munter, Ohio State University. (Chemistry, part-time).

Headquarters were established in the Ohio hatchery at Put-in-Bay. As in the earlier years additional space and equipment were made available in the Franz Theodore Stone Laboratory. The first observations were made on May 14; the last on October 22. With minor exceptions the full staff was on duty from June 15 to September 15, and in the remaining time the program was carried on by W. M. Tidd and the writer.

The general plan of investigation was the same in 1929 and 1930. This will be discussed in later pages of the introduction, together with the location of stations, frequency of observation, and similar details. In addition to the observation of physical conditions at the time of sampling, samples were taken regularly for chemistry, phytoplankton, zooplankton, and bottom organisms. Bacteriological samples were taken at less frequent and regular intervals. The details of methods employed in the field and laboratory will be presented in the various chapters dealing with results.

Season of 1930

In 1930 field investigations on fishes were discontinued, and the fisheries staff was engaged in studies of the collections made in the two preceding years. The limnological program was continued along essentially the same lines as in 1929.

The scientific staff was as follows:

E. L. Wickliff, Chief, Bureau of Scientific Research, Ohio Division of Conservation. (Director of the Survey).
Stillman Wright, United States Bureau of Fisheries. (In charge of limnological investigations).
C. J. Munter, Ohio State University. (Chemistry).
Doris Ann Wright, Ohio Division of Conservation. (Zooplankton).
Barbara Metz, Winthrop College. (Phytoplankton).
Elbert H. Ahlstrom, Marietta College. (Bottom organisms).
Lee S. Roach, Ohio University. (Bottom organisms).

Headquarters were established at the Franz Theodore Stone Laboratory on Gibraltar Island, Put-in-Bay. The first observations were made on April 4, and the last on October 3. The full staff was in residence from June 15 to September 15; in the remaining time the program was carried out on a reduced schedule. Aside from the discontinuance of bacteriological work, and expansion of chemical work, the program in this year was essentially the same as in 1929.

In the following section will be given the plan of investigation followed in 1929 and 1930, for the reason that it serves as an introduction to most of the chapters of the report. In the years prior to 1929, the plan was somewhat different. However, in presenting data for the earlier years, those will be selected which fit into the scheme of 1929 and 1390. In that way it is possible to attain a degree of uniformity in presentation.

Plan of Investigation

The general plan of investigation followed in 1929 and 1930 was based on a knowledge of the lake gained in the earlier years. It had been found that there was definite evidence of heavy pollution near the mouths of certain tributary streams, and that the intensity decreased rapidly with increased distance from the source of pollution. The open waters of the lake, far from large sources of domestic and trade wastes, were free from the more obvious evidences of pollution. Here, only bacteriological analyses were adequate to show that the lake was contaminated by sewage.

It seemed advisable, then, to divide the area into sections, and to make parallel studies in each section. The way in which the lake was divided is shown in Figure 1. Western Lake Erie was defined arbitrarily as that part of the lake west of a line which touches the Canadian shore at 82° 30' west longitude, runs due south to the International Boundary, and then to the west end of Cedar Point. Western Lake Erie was divided into 5 sections as shown on the map. Obviously the limits of the sections are not natural; of necessity they were determined arbitrarily. The sections have been designated by names which described their positions in general: Island, Portage River, Maumee Bay, River Raisin, and Detroit River.

Early in the season of 1929, a small number of stations were established, and with minor exceptions these were maintained in the following year also. They may be designated as "regular stations", as they were visited at fairly regular intervals. In addition to the regular stations, a large number of special stations were established for special purposes. In order to avoid confusion, these special stations are not shown in Figure 1. Their location will be given in the text or in tables at the proper places in the report. Many of them are shown in Figure 23.

Data on the location, depth, and type of bottom of the regular stations, by sections, follows:

Island Section

Station 18. Location, 3/8 mile SE. 1/8 E. of Mill Point, east shore of Pelee Island. Depth, 7.3 meters. Bottom, sand and cobble stones.

Station 37A. Location, 3-3/4 miles ESE. 1/4 E. of Northeast Point, Kelleys Island. Latitude 41° 36.4'; longitude 82° 36.3'. Depth, 14.2 meters. Bottom, mud.

Station 59A. Location 11/16 mile E. of Marblehead Light. Depth, 9.3 meters. Bottom sandy mud.

Station 82. Location, 3 3/8 miles NE 1/8 N. of Port Clinton Light. Latitude, 41° 33.25'; longitude, 82° 53.4'. Depth, 6.9 meters. Bottom, mud. (This station was not visited in 1930).

Station 158. Location, 1/2 mile WSW. 1/2 W. of end of county road on shore of Stone's Cove, South Bass Island. Depth, 9.6 meters. Bottom, mud.

Station 68. Location, 5/16 mile N. of Niagara Reef gas buoy. Latitude, 41° 40.5'; longitude, 82° 58.3'. Depth, 9.7 meters. Bottom, sandy mud. (This station was not visited in 1930).

Station 75. Location, 1 3/8 miles E. of West Sister Island Light. Depth, 9.4 meters. Bottom, mud. (This station was not visited in 1930).

Station 72. Location, 4 miles NW 3/4 W. of Station 68. Latitude, 41° 42.6'; longitude, 83° 02.1'. Depth, 9.5 meters. Bottom, mud. (In 1930 Stations 68 and 75 were abandoned and Station 72 substituted for them).

Station 8F. Location, 6 1/2 miles NNE. 7/8 E. of East Sister Island. Latitude, 41° 53.6'; longitude, 82° 47.2'. Depth, 12. 1 meters. Bottom, mud.

Portage River Section

Station 159. Location, 1/4 N. of Port Clinton Light. Depth, 3.5 meters. Bottom, sand.

Maumee Bay Section

Station 250. Location, at red gas buoy at the mouth of Maumee River. 8 3/8 miles SW. by W. 1/8 W. of Toledo Harbor Light. Depth, 3.0 meters. Bottom, mud.

Station 252. Location, at Toledo Harbor Range Lights, 4 miles SW. by W. 1/8 W. of Toledo Harbor Light. Depth, 3.9 meters. Bottom, mud.

Station 254. Location, 1/8 mile SE of Toledo Harbor Light. Depth, 6.2 meters. Bottom, mud.

River Raisin Section

Section 117. Location, 2 miles ESE. 1/8 E. of Monroe Light at the Mouth of River Raisin. Depth, 6.1 meters. Bottom, sand and gravel.

Detroit River Section

Station 126. Location, 2 1/4 miles S. by W. 3/4 W. of Detroit River Light. Depth, 7.0 meters. Bottom, mud and sand.

Station 134. Location, 6 1/8 miles W. of Middle Sister Island. Latitude, 41° 50.9'; longitude, 83° 07.3'. Depth, 10.0 meters. Bottom, mud.

It was planned originally to make observations at each station in each half-month period during the season. For various reasons this program could not be adhered to strictly. On a lake as large as Lake Erie, winds commonly give rise to seas which are unfavorable for the carrying out of limnological work. In 1930 the program was followed with few irregularities and the data of that year have been found most useful for the purposes of the report.

Ordinarily, field observations and samples were taken in the morning, and the boat returned to the laboratory about noon to permit analysis of the samples in the afternoon. For the more distant stations, that is, those at the extreme western end of the area, a run was made to Toledo or Amherstburg in the afternoon, and samples were taken the following morning. Where possible, stations were located by means of landmarks. In the case of stations far from land, they were reached by running the boat at a known speed for the proper length of time along the proper course. While this method does not make possible the occupation of exactly the same point on successive attempts, experience showed that it was adequate for the needs of the investigation. For details concerning methods employed in the field and laboratory, the reader is referred to the various chapters in the body of the report.

Scope of the Report

Following completion of field work in autumn of 1930, the Bureau of Fisheries assumed the responsibility of assembling the data and preparing a report of the investigation. Owing to the great diversity of subject matter and of contributing workers, the task of writing a complete and unified report required a long period of time. Dr. Lewis H. Tiffany collaborated in writing the chapter on phytoplankton, and Dr. Wilbur M. Tidd in writing the chapter on zooplankton.

The report is based principally on data obtained in the seasons of 1929 and 1930. From the data of 1928, certain ones have been selected for inclusion. Selection was based primarily on the possibility of fitting the data into the plan of presentation for those of 1929 and 1930. No data of 1927 have been included. Those of 1926 have been treated as published data, and where possible, introduced to supplement the data of later years.

In preparing the report, it appeared advisable to review the scientific literature on all of the Great Lakes, rather than that on Lake Erie alone. Although the lakes other than Lake Erie are almost entirely unknown from the point of view of modern limnology, there are a large number of papers which would be of value in planning future investigations. Since the literature is widely scattered, and, in some cases, difficult of access, it seemed desirable to review it in this report. Accordingly, many of the chapters or sections of chapters contain a brief account of previous investigations in the Great Lakes. In some cases the review consists merely of a citation of literature; in other cases results were introduced. No attempt was made to cite all of the literature encountered. Where possible and desirable, reference was made to reports which contain extensive literature lists. For example, the reader will be referred to Horton and Grunsky (1927) for details and literature concerning hydrology, and to Leverett and Taylor (1915) for geology. In this way it was possible to attain a degree of completeness without undue increase in the size of the report. It is quite probable that some papers have escaped notice, but it is hoped that the reader will find reference to all of those of importance by use of "key references", such as those mentioned above. Papers on ichthyology and fishery science have been included only when they had immediate bearing on the problem in hand. Forthcoming reports will deal with these subjects in detail. None of the several papers on limnological investigations in the Great Lakes published since 1933 is included in the bibliography, and the list for 1933 is probably incomplete.

Acknowledgments

In 1926, the survey was in charge of Dr. R. C. Osburn, Director of the Franz Theodore Stone Laboratory, and he was closely associated with the work in following years. After 1926, the investigation was under the general direction of Mr. E. L. Wickliff, Chief of the Bureau of Scientific Research, Ohio Division of Conservation. Participation of the U. S. Bureau of Fisheries in 1929 and afterward was under the direction of Dr. John Van Oosten, In Charge of Great Lakes Fishery Investigations. It is a pleasure to acknowledge the essential part played in the investigation by these men.

In an investigation of the kind reported here, covering five seasons of field study and several categories of aquatic biology, it is only natural that those intimately associated with the work would seek aid from others in a position to render it. The number of persons who have made contributions of general or professional nature is great. A large measure of the success of

the undertaking is owing to such contributions, and they are gratefully acknowledged. A number of these have been of such outstanding importance as to require individual mention.

Although the Franz Theodore Stone Laboratory was one of the cooperating organizations engaged in the survey, it is fitting that acknowledgment of the important role of the laboratory and its staff be made to the director, Dr. R. C. Osburn.

A number of employees of the Ohio Division of Conservation were associated with the survey for the entire period. Harry C. Crossley and George F. Miller, as well as the men working under their direction at Sandusky and Put-in-Bay, extended many courtesies and material aids to the scientific staff. Special thanks are due Robert Shortliff, captain of the Investigator in 1928, 1929 and 1930, who rendered services far beyond the dictates of duty.

Many scientific investigators in institutions not associated with the survey made valuable contributions. Those who performed services in a restricted field will be mentioned in the introductions to the appropriate chapters of the report. Professor Chancey Juday, of the University of Wisconsin, has corresponded frequently with the writer concerning the progress of the work, and it would be difficult to overestimate the value of his counsel. Professor Jacob Reighard, Professor Emeritus, of Zoology, University of Michigan, generously permitted the use of data from his unpublished report on pollution in the lower part of River Raisin. Dr. Paul S. Welch of the Zoology Department, University of Michigan, loaned a number of pieces of equipment, and was very helpful in an advisory capacity. Dr. Carl L. Hubbs, of the Museum of Zoology, University of Michigan, loaned chemical equipment and made many helpful suggestions. Finally, the writer wishes to acknowledge the innumerable services rendered by his colleagues in the Ann Arbor office of the United States Bureau of Fisheries.

PHYSICAL LIMNOLOGY OF WESTERN LAKE ERIE

Hydrography

Lake Erie is one of a series of six large lakes known as the Great Lakes of North America. The lakes lie in the drainage basin of St. Lawrence River, and constitute the largest group of connected bodies of fresh water in the world. Lake Superior, the largest and deepest of the lakes, forms the head of the system (Table 1). It discharges into Lake Huron through St. Mary's River. Strictly speaking, Lakes Michigan and Huron constitute one lake, for their surfaces have the same elevation, and the lakes are intimately connected by the Straits of Mackinac. Lake Huron is drained by St. Clair River, which discharges into Lake St. Clair, the smallest and shallowest lake of the system. Detroit River is the connecting link between Lake St.

Clair and the next lowest lake, Lake Erie. Lake Erie discharges into Lake Ontario through Niagara River, in the course of which the water passes over Niagara Falls. St. Lawrence River carries the water of Lake Ontario to the sea.

In common usage the term Great Lakes is restricted to the five largest lakes, because of the relatively insignificant size of Lake St. Clair. Lake St. Clair may be regarded merely as an expansion of the river connecting Lake Huron and Lake Erie.

Of the five Great Lakes, Lake Erie exceeds only Lake Ontario in area.[1] Including Detroit River, its area is 9,940 square miles (25,745 square kilometers), and the International Boundary divides the lake in almost exactly equal parts (Fig. 2). The entire drainage basin has an area of 34,680 square miles (89,821 square kilometers). The greatest length of the lake, along a straight line clearing point Pelee and Long Point is 241 miles (388 kilometers) and the greatest breadth, between Ashtabula and Point Talbot, is 57 miles (92 kilometers). The principal axis of the lake has an approximately ENE-WSW trend for most of its length, but west of Point Pelee the trend is nearly ESE-WNW.

The southern shore is remarkably regular, with Ottawa Peninsula and Sandusky Bay toward the west, and Presque Isle toward the east as the only notable features. On the north there are three proimnent peninsulas to break the monotony of the otherwise regular shore line. They are Point Pelee on the west, Pointe aux Pins some miles eastward, and Long Point near the east end of the lake. Point Pelee and Long Point are so prominent that a map of the lake naturally divides itself in three sections; a large central section, with smaller sections at either end. The shores are low for the most part, especially near the west end. Although the number of tributary rivers is large, only one, Detroit River, is important in the amount of discharge. The western half of the northern shore has very few streams entering the lake. At the extreme eastern end, the lake discharges into the Niagara River, which carries the water northward to Lake Ontario. For an account of the topography of the shores, and the underlying geological structures, the reader is referred to Leverett (1902) and to Pegrum (1929).

Lake Erie is the shallowest of the five Great Lakes and the only one whose bottom does not extend below sea level. The deepest point recorded is 210 feet (64 meters) below standard low water (570.00 feet (173.78 meters) above mean sea level), which has been adopted for the charts of Lake Erie issued by the United States Lake Survey. The mean lake level during the period 1860-1930 was 2.44 feet (0.744 meter) above standard low water, hence, soundings made on the lake will normally be greater than those recorded on the charts. The division of the lake into three sections, which is so evi-

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[1] A detailed description of Lake Erie, as well as of the other lakes of the St. Lawrence River system, appears annually in a bulletin entitled "Survey of Northern and Northwestern Lakes", published by the United States Lake Survey, at Detroit. The hydrographic data given here are taken from Bulletin No. 40, published in 1931, and from charts issued by the Survey.

Table 1.- Hydrographic data on the Great Lakes, taken from Bulletin 40 of the U. S. Lake Survey and from files of the survey

Lake	Elevation in feet, mean, 71 years		Length in miles (right line)	Breadth in miles (right line)	Depth in feet		Area in square miles	
	Above mean sea level	Above succeeding lake			Maximum	Mean	Lake	Entire drainage basin
Superior	602.23	21.30	350	160	1,290	----	31,820	80,900
Michigan	580.93	----	307	118	923	276	22,400	69,040
Huron	580.94	5.45	206	101	750	----	23,010	72,420
St. Clair	595.49	3.05	26	24	23	10.3	460	6,420
Erie	572.44	326.32	241	57	210	63.9	9,940	34,680
Ontario	246.12	----	193	53	738	----	7,540	34,630

dent on a map, is equally evident in a profile of the lake basin. That part of the lake east of a line between Presque Isle and the base of Long Point has a relatively deep basin with a considerable area of greater depth than 120 feet (36.6 meters). South and east of Long Point there is a small area with depths exceeding 180 feet (54.9 meters), within which is found the maximum depth of the lake. The large central section of the lake has a broad flat basin with a maximum depth of 84 feet (25.6 meters). From Point Pelee westward the water shoals rapidly. The entire western basin is like a shelf raised well above the level of the central basin. The maximum depth recorded is 54 feet (16.5 meters), but only a small part of the area exceeds 36 feet (11.0 meters) in depth. In the eastern part of this section is found a number of islands, which, with Point Pelee on the north and Ottawa Peninsula on the south, tends to make the basin distinct from the central basin toward the east. The mean depth of the entire lake is 63.9 feet (19.5 meters).

The present investigation is concerned only with Western Lake Erie (Fig. 3). While this part of the lake is partially separated from the remainder by the presence of the natural barriers mentioned above, the line of separation is necessarily not an exact one. For the purposes of this report, the line of separation is defined arbitrarily as a line which touches the Canadian shore at 82° 30' west longitude, runs due south to the International Boundary, and thence to the west end of Cedar Point. The part of the lake west of this line is considered as Western Lake Erie, and includes Sandusky Bay and Maumee Bay. There is no sharp line of demarcation between Detroit River and the lake; the one which has been selected is a straight line from the mouth of Huron River through Bar Point Lightship to the Canadian shore at Bar Point.

The area of Western Lake Erie as defined above is 1,397 square miles (3,618 square kilometers). This area is reduced to 1,317 square miles (3,411 square kilometers) by the exclusion of Sandusky Bay and the five largest islands. Its length, from Monroe Light to the intersection of the International Boundary with 82° 30' west longitude, is 47 miles (75.7 kilometers); and its breadth, from Port Clinton Light to Leamington Light, is 39 miles (62.8 kilometers).

Sandusky Bay, the largest well-defined bay of the lake, has an area of 54.4 square miles (140.9 square kilometers). According to Moseley (1904) it was formed when the level at the west end of the lake raised and drowned the mouth of Sandusky River. The bay is almost shut off from the lake by the presence of two sand spits, Cedar Point and Sand Point. The long axis lies in an east-west direction, and near the middle of its length the bay is divided into two sections by Danbury Point jutting from the north shore toward Martin Point on the south shore. Except where artifically deepened for navigation the bay is shallow, not exceeding 13 feet (4 meters) in the eastern part, or 7 feet (2 meters) in the western part. The mean depth is about 5 feet (1.5 meters). Sandusky River, the most important tributary enters the bay near its western extremity, and a number of smaller streams enter in the same locality. The mean discharge of Sandusky River near Fremont, Ohio, for the six year period 1925-1930 was 1,050 cubic feet (29.7 cubic meters) per second (United States Geological Survey, 1929-1932).

Sandusky Bay is bounded on the north by Ottawa Peninsula. The peninsula is narrow at the base and expands into two prominent headlands, Marblehead on the east and so-called Catawba Island (a peninsula) on the west. Between the two headlands, on which the shores are relatively steep and rocky, there is an expanse of low ground in which are the lagoons known as East Harbor and West Harbor.

Just west of Ottawa Peninsula, Portage River empties into the lake. It has the usual characteristics of a drowned valley. For ten miles above its mouth it is very broad, but at the mouth it narrows sharply due to the presence of a sand spit on the west bank. The discharge of Portage River is not known but it is certainly small, for the current reverses periodically in much the same way that Krecker (1928 and 1931) has described for East Harbor and West Harbor. According to reports of fishermen at Port Clinton, the frequency of reversal is not constant, but depends upon direction and intensity of the wind. With a strong on-shore wind the current flows up-river, often for many hours, in which case the water level rises for several miles back from the mouth. When the wind is offshore, the current flows outward. But even in calm weather the reversals persist and not infrequently take place several times a day. During the present investigation reversing currents have been observed also in Maumee River and River Raisin, and they are probably common to all the tributaries of Western Lake Erie with the exception of Detroit River.

Between the mouth of Portage River and Maumee Bay the shore is low and regular, and much of the bordering land is marshy. The only tributaries worthy of mention are Toussaint River and Crane Creek. They are smaller than Portage River but have the same general characteristics. Maumee Bay, at the southwest corner of the lake, is partially enclosed by two peninsulas, Little Cedar Point on the east, and the long, narrow Bay Point on the northwest. The south shore of the bay is regular, but the west shore is much indented, and fringed by small islands. Except where it has been deepened artificially the bay is very shallow, not exceeding 8 feet (2.4 meters). A steamship channel has been dredged from the mouth of Maumee River to a point 9 miles (14.5 kilometers) distant on a NE by E 1/8 E course. The entrance to Toledo harbor is thus some distance outside of the natural limits of Maumee Bay. The channel has a depth of 21 feet (6.4 meters). Maumee River empties in at the apex of the triangular bay. At its mouth the river is more than a half mile wide but the discharge is meager. Data on the combined discharge of Maumee River and Miami-Erie Canal at Waterville, Ohio, about 25 miles above the mouth, are available for the nine years prior to September 30, 1930 (United States Geological Survey, 1925-1932). The mean discharge for the nine-year period was 5,417 cubic feet (153.4 cubic meters) per second. Ottawa River empties into Maumee Bay immediately west of the mouth of Maumee River.

The west shore of the lake is less regular than the south shore, but is generally low with sandy beaches. A notable exception is stony Point, which is located a few miles north of the mouth of River Raisin. The tributaries are rather numerous but most of them are small in size (See Sherzer, 1900). River Raisin empties into the lake near Monroe, Michigan. The river has built a considerable delta with a number of dis-tributaries, some of which

no longer connect with the lake. The principal outlet is the United States Ship Canal. Reighard, in an unpublished report, pointed out that all of the streams along this shore have wide and deep channels near their mouths, and that the current in River Raisin undergoes frequent reversals. On August 14, 1920, the direction of the current changed five times between 8:00 A.M. and 5:15 P.M. Reversals were noted during the present investigation also, but observations were not made over long enough periods to determine their frequency. The discharge of River Raisin has not been measured, but McNamee (1930, p. 56) estimated the mean annual rate of discharge at 0.60 cubic feet per second per square mile, which, with the drainage area of 1,125 square miles (2,914 square kilometers), would give a mean annual discharge of 675 cubic feet (19.1 cubic meters) per second.

Huron River empties into the lake at the northern boundary of the west shore. The mean annual discharge at Flat Rock, seven miles from the mouth, for the six-year period, 1905-1909, was 670 cubic feet (19.0 cubic meters) per second (Sherzer, 1913, page 117).

Detroit River is 4.25 miles (6.8 kilometers) wide at the mouth. Its length from Windmill Point to Bar Point Lightship is about 28 miles (45 kilometers). Near its head the river is divided by Peach Island and Belle Isle. Below Belle Isle the channel is deep,the banks are steep, and the current velocity is about 1.5 miles (2.4 kilometers) per hour. At the head of Fighting Island, the river broadens and becomes shallower. There are a number of islands in the lower river; the largest is Grosse Isle, near the United States shore. Bois Blanc Island, much smaller than Grosse Isle is near the Canadian shore opposite Amherstburg. A short distance above this island the mean current velocity is 3 miles (4.8 kilometers) per hour, and the maximum is about 6 miles (9.7 kilometers) per hour. The discharge of St. Clair River is 204,000 cubic feet (5,777 cubic meters) per second at the mean stage of Lake Huron and Lake Erie, with an increase of 19,700 cubic feet (558 cubic meters) per second per foot rise of Lake Huron, without change in Lake Erie. The discharge of Detroit River is only slightly greater than that of St. Clair River on the average. The amount discharged into Niagara River from Lake Erie is almost the same; it is 206,00 cubic feet (5,834 cubic meters) per second at mean stage, with an increase of 22,100 cubic feet (626 cubic meters) per second per foot of rise of lake level.

Lower Detroit River has been deepened artificially to permit the passage of large vessels. At the level of Bois Blanc Island there are two channels, but these join at Bar Point Lightship and continue as one to Detroit River Light (Fig. 1). Here the channel divides to form a west or downbound, and an east or upbound, channel. The former extends in a S. by W. direction 3.9 miles (6.3 kilometers), and the latter extends in a S. by E. 3/8 E. direction 2.25 miles (3.6 kilometers).

The north shore of Western Lake Erie is almost free from irregularities. The beaches are generally sandy, and in a few places there are high bluffs of glacial material back from the beach. There are few tributary streams and

none of them is large. Point Pelee is the most prominent shore feature. It is a peninsula which projects southward into the lake for many miles. The base is broad, but it tapers gradually and ends in a sand bar which is curved toward the east.

There are five islands in the lake with an area exceeding one square mile (2.59 square kilometers). Pelee Island, the largest has an area of 16.3 square miles (42.2 square kilometers), and lies entirely in Canadian waters south and west of Point Pelee (Fig. 4). Kelleys Island, the second largest, lies south of Pelee Island, and has an area of 4.4 square miles (11.4 square kilometers). The remaining three make up the group known as the Bass Islands; North, Middle, and South Bass. They lie in a north and south line some miles west of Pelee and Kelleys; and South Bass lies 3 miles (4.8 kilometers) north of the mainland at Catawba Island. North Bass has an area of 1.1 square miles (2.8 square kilometers); Middle Bass an area of 1.2 square miles (3.1 square kilometers); and South Bass 2.4 square miles (6.2 square kilometers). South Bass Island is commonly called Put-in-Bay from the harbor and village on the north side. At the entrance to the harbor lies Gibraltar Island, which is only a few acres in extent. Other small islands near this group are Ballast, Starve, Green, Rattlesnake, Sugar, Hen, Big Chicken, and Little Chicken. Middle Island is situated between Pelee and Kelleys, and another of small size is Mouse Island, just off Scott Point on Catawba Island. The Sister group is composed of four small islands, West, Middle, and East Sister, and North Harbor Island (See maps, Fig. 3 and 4). The geologic features of some of the islands and parts of the south shore have been discussed by Newberry (1874).

In general, the slope of the bottom in Western Lake Erie is very gentle. This is particularly true along the south and west shores, where the 21 foot (6.4 meter) contour line is, in places, 5-7 miles (8-11 kilometers) from the beach. On the north shore the slopes are less gentle and the 21 foot contour is usually within one mile of the beach. Most of the islands have considerable areas of shallow water about them. In addition there are a number of reefs and shoals. The most conspicuous of these are Niagara Reef, Chickenolee Reef, Kelleys Island Shoal, Kelleys Island South Shoal, Gull Island Shoal, Middle Ground, and Southeast Shoal. (See Fig. 3 and Fig. 4). It is the presence of the islands and shoal areas between Point Pelee and Ottawa Peninsula which forms a partial barrier to the movement of water between Western Lake Erie and the rest of the lake.

Insofar as it is possible to speak of a depression in the basin, it is placed asymmetrically toward the north, as indicated by the 33 foot (10.1 meters) contour line on the map. Within this line there is a small area north of Pelee Island with a depth of 36 feet (11.0 meters), which connects with deeper areas to the east by means of a trough between Middle Ground and Southeast Shoal. A small area of relatively deep water is found between the Bass Islands and Pelee Island. It appears as a trough which extends westward between Gull Island Shoal and Kelleys Island Shoal, and then turns northward. Much of this trough is 42 feet (12.8 meters) deep, and there is a small hole, south of Gull Island Shoal, which has a depth of 54 feet (16.5 meters). The mean depth of Western Lake Erie exclusive of Sandusky Bay is 24.6 feet (7.5 meters).

The volume of Western Lake Erie exclusive of Sandusky Bay is 6.15 cubic miles (25.58 cubic kilometers). This figure was obtained by the use of Penck's formula (Juday, 1914, p. 122). The volume of the entire lake is 120 cubic miles (499 cubic kilometers), or about 20 times the volume of Western Lake Erie.

Fluctuations of Lake Level

Fluctuations owing to changes in volume

The volume of water in Lake Erie is changing constantly, and these changes are reflected in fluctuations of the mean lake level. There are five factors whose interrelationships determine changes in volume: (1) inflow from the upper lakes: (2) run-off from the drainage basin; (3) rainfall on the lake: (4) evaporation; and (5) outflow through Niagara River and artificial diversion channels. The problem of evaluating these factors and determining their interrelationships is one of extreme complexity; and by reason of the diversions at Chicago since 1900 the whole question of lake levels has become highly controversial. It is neither possible nor desirable to enter into a discussion of the problem here. Of the many reports on the subject, the volume by Horton and Grunsky (1927) will be found valuable because of its completeness and the inclusion of a bibliography. Disregarding, then, the factors which determine volume, and hence mean lake level, some of the data on observed fluctuations will be considered briefly.

Seasonal fluctuations

Hayford (1922, p. 112) stated that "the actual variation of the mean elevation of the whole surface of any one of the Great Lakes is, as a rule, as much as 0.01 foot in two days, that it is frequently more than 0.02 foot in 24 hours, and that on rare occasions it may exceed 0.08 in that period." Such small variations are not evident to the eye of an observer because they are masked by transient disturbances of the level, but since the variations are principally in one direction for many days, the change in level, by accumulation, finally becomes evident without the use of special instruments.

For many years the United States Lake Survey has been keeping an accurate record of levels in the Great Lakes by means of gauges placed at strategic points along the shores. In Table 2 and Fig. 5 are shown the averages of the monthly mean levels at Cleveland, Ohio, for the period 1860-1930. It may be seen that, on the average, the level has been low in winter and high in summer; the lowest month has been February and the highest June. It should not be assumed that the low point always occurs in February or the high point in June During the 71-year period the low point has occurred also in January, March,

Table 2.- Averages of monthly mean levels of Lake Erie at Cleveland, Ohio, for the Period 1860 - 1930

Month	Feet above mean tide at New York
January	571.93
February	571.86
March	572.04
April	572.58
May	572.92
June	573.09
July	573.05
August	572.87
September	572.61
October	572.29
November	572.03
December	571.96
Annual mean	572.44

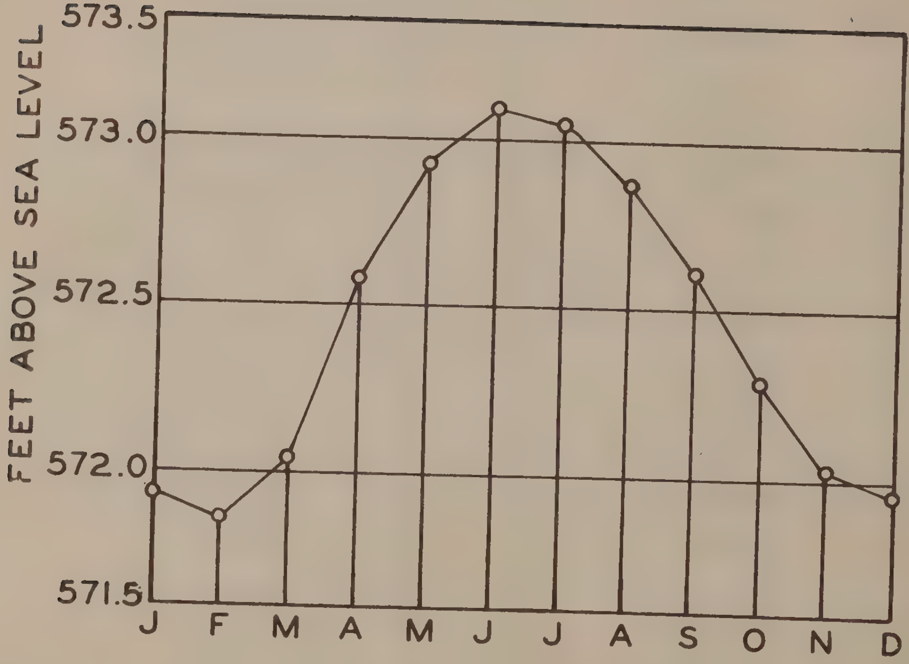

Fig. 5--Averages of monthly mean lake levels at Cleveland, Ohio, for the period 1860-1930. Data taken from Table 2.

October, November, and December; and the high point in March, April, May, July, August, September, and October. For this reason the range of the averages from high to low (1.23 feet) does not give the true mean range for the period. The mean range, determined from the ranges of the individual years, is 1.57 feet. The maximum range (2.5 feet) occurred in 1917, and the minimum (0.87 foot) in 1895. The highest monthly mean stage since 1860 was recorded for June, 1876 (574.52 feet). The highest stage for which we have a reliable record is that of 1838, when the water reached a height of 575.11 feet. The lowest monthly mean level since 1860 was recorded for February, 1926 (569.90 feet).

Annual fluctuations

The annual mean lake level for any one year may be calculated from the monthly means for that year. In Table 3 are shown the annual mean levels at Cleveland for each year of the period 1860-1930. For a detailed discussion of the fluctuations from year to year the reader is referred again to Horton and Grunsky (1927). The general subject of lake levels has been discussed by Shuman (1931).

Fluctuations in glacial and postglacial time

Lake Erie has had a complex geological history. Since its origin as Lake Maumee at about 790 feet above sea level, it has stood at no less than 26 levels long enough to establish recognizable beaches, the lowest one at a height of about 540 feet, or 32 feet below the mean level of recent times. The reader may refer to Leverett and Taylor (1915) for a detailed account of the lake's history. In passing, it may be mentioned that Moseley (1899 and 1904) showed that the level of Western Lake Erie has risen in recent times. The evidence rests in part on the existence of drowned valleys such as Sandusky Bay, and on the presence of submerged stalactites in the caves of South Bass Island. Moseley estimated the rate of rise at 2.14 feet per century for at least four centuries. He believed that the rise was caused by progressive tilting of the basin toward the west. Taylor (Leverett and Taylor, 1915, p. 333) cast doubt upon this as an explanation of recent changes, stating that the drowning effects, at least to depths of 10 or 15 feet, are probably due to a return of the large volume of discharge to the Buffalo outlet following the Nipissing stage of the Great Lakes. However, in an interview with the writer on September 7, 1932, Professor Leverett stated that it is now generally recognized that tilting of the basin is still in progress.

Transient fluctuations

If all external disturbing forces were removed, determination of the mean lake level at any one time could be made from one reading of the gauge. In reality, external forces are acting almost constantly upon the surface of

Table 3.- Annual mean levels of Lake Erie at Cleveland, Ohio, for the period 1860 - 1930. Levels in feet above mean tide at New York

Year	Level	Year	Level	Year	Level	Year	Level
1860	573.50	1878	573.29	1896	571.39	1914	572.17
1861	573.58	1879	572.53	1897	571.96	1915	571.68
1862	573.69	1880	572.77	1898	572.14	1916	572.29
1863	573.40	1881	572.61	1899	571.93	1917	572.73
1864	572.80	1882	573.48	1900	571.94	1918	572.25
1865	572.44	1883	573.27	1901	571.39	1919	572.77
1866	572.58	1884	573.34	1902	571.84	1920	571.91
1867	572.61	1885	573.24	1903	572.39	1921	572.30
1868	572.23	1886	573.34	1904	572.54	1922	572.00
1869	572.65	1887	573.31	1905	572.17	1923	571.41
1870	573.28	1888	572.61	1906	572.26	1924	571.68
1871	572.69	1889	572.38	1907	572.73	1925	570.87
1872	571.73	1890	573.05	1908	572.69	1926	570.98
1873	572.44	1891	572.15	1909	572.15	1927	571.58
1874	572.95	1892	572.14	1910	571.87	1928	571.99
1875	572.28	1893	572.09	1911	571.47	1929	573.10
1876	573.70	1894	572.10	1912	572.02	1930	573.07
1877	572.88	1895	571.17	1913	572.95	Mean	572.44

the lake, disturbing the hydrostatic equilibrium and necessitating an almost continuous record to approximate the true mean lake level. The effect of the disturbing agents is felt long after they have ceased to operate, so that, even in their absence for a time, the level at any one point continues to fluctuate.

Atmospheric pressure is the agent responsible for most of the disturbances. When the atmospheric pressure is different on different parts of the lake, water is forced from the area of high pressure to the area of low pressure. According to Hayford (1922), this direct effect of pressure, while by no means negligible, is less important than its indirect effect in producing winds. Waves are the most obvious disturbances of the surface resulting from wind action. Wind is also a powerful agent in setting up currents to leeward, where the water piles up against the shore. Seiches prolong the time during which disturbances resulting from differential atmospheric pressure and winds affect the lake, and currents from any cause have a tendency to disturb the normal hydrostatic equilibrium although the effect is probably not great for a majority of currents. Tides also have the same tendency, but Hayford regarded them as of minor importance. In the more detailed discussion of transient fluctuations which follows, differential atmospheric pressure and winds are treated in the sections on seiches and currents. To discuss them separately would result in undue repetition.

Waves

Up to the present, the effects of transient disturbances on determinations of the mean lake level alone have been mentioned. Because of the construction of the automatic level gauges, waves do not affect such determinations, but they have other effects of importance. The extreme shallowness in the western part of the lake tends to make large waves break and mix the water to considerable depths. Since currents also result in mixing, it is impossible to determine how much is due to waves, but it seems probable that in Western Lake Erie this factor alone would be sufficient to explain occasional complete mixing from top to bottom. The mixing results in the usual homothermous condition of the water, permits free interchange of gases, and prevents long-continued stratification of the completely passive plankters. The violent action of waves on shores and reefs tends to break up the colonial algae and undoubtedly causes the death of many delicate organisms. Waves also add to the turbidity of the water, especially in the very shallow areas.

There have been no exact measurements of waves on Lake Erie; in fact the only accurate data available for the Great Lakes are those of Gaillard (1904, p. 81) for Lake Superior at Duluth. The largest waves observed by him in the ship canal had a height of 23 feet (7 meters) and a length of 275 feet (84 meters). From the accounts of navigators, Gaillard estimated that at rare intervals in the deep water of Lake Superior there are waves 20 to 25 feet (6.1 to 7.6 meters) in height and 275 to 325 feet (84 to 99 meters) in length. It is probable that waves never attain that size in Lake Erie. According to Gaillard the highest waves at Buffalo were reported to be 10 feet (3.0 meters) in height.

Seiches

Rapid fluctuations of level in the Great Lakes were noted at a very early time, certainly before the middle of the seventeenth century (Thwaites, 1898, p. 61)[2]. Their cause was a subject of speculation for many years; some regarded them as tides comparable to those in the ocean, while others denied the existence of tides. It is now known that the fluctuations were the result of seiches.

During the present investigation, no study was made of seiches and the subject will not be discussed in detail. The reader interested in seiches in the Great Lakes may refer to the following papers: Whiting (1831), Whittlesey (1851 and 1875), Lachlan (1855), Comstock (1872), Le Conte (1884), Perkins (1893), Harrington (1895), Denison (1897), Borman (1912), and Crohurst and Veldee (1927). In addition the following concern Lake Erie especially: Reed (1899), Henry (1899 and 1902), Harris (1902), Endrös (1908), McLaughlin (1911), Jackson (1912), Farwell (1925), Hayford (1922), Krecker (1928 and 1931), Parmenter (1929), and Green (1933).

Our knowledge of the periods and amplitudes of seiches in Lake Erie may be summarized briefly as follows: The uninodal longitudinal seiche has a period of very nearly 14.2 hours and the uninodal transverse seiche a period of about 2.6 hours. There is some evidence of the presence of binodal, trinodal and quadrinodal longitudinal seiches of 8.8, 5.7 and 4.1 hours respectively. There is abundant evidence for the existence of other seiches of shorter periods, operating along more localized axes. The amplitude of the seiches varies from a few centimeters to nearly 3 meters, and for any single type of seiche varies according to the magnitude of the original disturbing force.

Tides

Tides in the Great Lakes are so small that they must be considered as minor disturbances of the levels. Seiches commonly cause fluctuations several times greater than the highest tides. Tides have been observed at Milwaukee and Chicago in Lake Michigan, and at Duluth and Marquette in Lake

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[2] The Jesuit Relations contain many notes on natural phenomena observed by the missionaries (see Index, Vol. 72 and 73). For others see the index to Wisconsin Historical Collections, Vol. XXI. The whole subject of early exploration on the Great Lakes is treated in detail by Kellogg (1925).

Superior. No attempt has been made to study them in Lake Huron and Lake Ontario, and the data on those of Lake Erie are too meager to prove their existence, but there is every reason to believe that careful study would reveal the tides of these lakes. Those who may be interested in the data on this subject should refer to Whittlesey (1859), Graham (1861), Comstock (1872 and 1873), Ferrel (1874), Harris (1907) Endrös (1908), and Krecker (1928). In addition, many of the early references given in the section on seiches give valuable historical information.

Currents

Currents in the Great Lakes other than Lake Erie have been discussed by Clark (1892-1893), Goodwin (1892), Harrington (1895), Nasmith and Adams (1914), Kindle (1915a and 1925), Judson (1909), Cooley (1913), McLaughlin (1912), Wasmund (1927-1928), and Deason (1932). Papers concerning Lake Erie particularly are: Harrington (1895), Fell (1910), McLaughlin (1911), Krecker (1928 and 1931), and Parmenter (1929).

The most important paper for our purpose is that of Harrington (1895), based on drift-bottle experiments in 1892, 1893, and 1894. Of the many bottles released in Lake Erie, 97 were reported found, and of these, nearly one-half had been released in Western Lake Erie. With regard to the currents in this part of the lake, he says:

> "At the western end of the lake the presence of Point Pelee, Pelee Island, and the archipelago to the south, cause certain variations, the principal one of which is the tendency of a whirl about the islands, noted in each of the lakes so far discussed. The numerous passages between the islands existing here, and the fact that the western end of the lake is nearly cut off by the point and islands, together prevent the development of a clear symmetrical whirl of the character found before. It is very much broken up into parts, and is possibly variable.".

In order to obtain more data on the surface currents, a series of experiments with drift bottles was carried out in May and June of 1928. The bottles were fitted with drags which tend to minimize the effect of winds, and were hence more effective than the simple bottles used by Harrington. Ninety-eight bottles were released and 54 were recovered.

For various reasons it seems unnecessary to present the detailed data on these experiments. The courses of many of the bottles are shown in Fig. 6. It will be noted that, in some cases, bottles set near each other were recovered at widely separated points. With few exceptions, the courses taken by the bottles in the experiments could be explained by reference to the data on wind direction. In most cases where the explanation was not evident, it was found that the bottles had been adrift a long time

or were adrift during a period of variable winds. Thus, while Harrington's data suggest great constancy in direction of the currents, the data of this study emphasize their inconstancy.

Without observation of the currents it could be assumed that the trend would be toward the east, because the gradient of the drainage system and the prevailing winds are toward the east. This eastward trend is necessarily modified locally by the islands and peninsulas in the eastern part of Western Lake Erie. The available data are inadequate to show all of these modifications, even during a period of westerly winds. Obviously, then, a tremendous number of drift-bottles would have to be released in order to determine the current system when the wind blows from other quarters.

Pending further investigation, it will suffice to say that the surface currents of Western Lake Erie flow prevailingly toward the east, but may flow in any direction under the influence of winds.

Meteorological Data

In order to give the reader some idea of the kind of weather which prevails in the region of Western Lake Erie during the period April to October, inclusive, a brief summary is presented here. Data on air temperature, rainfall, and wind at Sandusky, Ohio,[3/] are given in Tables 4, 5, 6, and 7. Normal values for the Sandusky station are based on records since 1877, except those for wind, which are based on records for the period 1921-1930. For the most part the data need no comment, but it may be worth while to call attention to a few points of special interest.

Considering the period of seven months in question, the years 1928 and 1929 were nearly normal with respect to temperature, but 1930 was warmer than normal. It will be shown later that the unusually high temperature in 1930 was reflected in higher water temperature in that year as compared with 1929, and that this difference had a noticeable effect on the plankton.

Rainfall in 1928 was nearly normal, but in 1929 it was excessive, while in 1930 it was well below normal. It has not been possible to find any definite relationship between the rainfall and any of the data collected during this investigation. However, the discharge of rivers other than Detroit River was greatly diminished in 1930.

In this region the wind blows prevailingly from the southwest. The mean velocity for the period of seven months was not far different in the three years, and in each year the mean velocity was below normal.

[3/] Data for Sandusky were obtained from the Monthly Meteorological Summary, issued by the United States Weather Bureau, and from the Annual Reports of the Chief of the United States Weather Bureau.

Table 4.- Monthly mean air temperatures at Sandusky, Ohio, April to October for the years 1928, 1929, and 1930, and the normal. Temperatures in degrees centigrade

Year	April	May	June	July	August	Sept.	Oct.	Mean Apr.-Oct.
1928	7.6	14.7	18.1	23.8	23.4	17.1	14.1	17.0
1929	11.1	13.9	19.6	23.3	20.6	18.7	11.6	17.0
1930	9.1	16.6	21.7	24.0	22.7	19.8	10.7	17.8
Normal	8.4	15.1	20.4	23.0	22.1	18.4	12.4	17.1

Table 5.- Monthly mean rainfall at Sandusky, Ohio, April to October for the years 1928, 1929, and 1930, and the normal. Rainfall in inches

Year	April	May	June	July	August	Sept.	Oct.	Total Apr.-Oct.
1928	2.34	1.92	5.26	4.04	2.92	0.73	3.05	20.26
1929	5.76	4.43	4.12	4.15	1.58	2.53	5.00	27.57
1930	2.70	2.79	2.94	1.34	1.16	3.88	1.07	15.88
Normal	2.55	3.15	3.49	3.44	3.16	2.96	2.44	21.19

Table 6.- Prevailing direction of the wind at Sandusky, Ohio, April to October for the years 1928, 1929, and 1930, and the normal

Year	April	May	June	July	August	Sept.	Oct.
1928	SW	SW	SW	SW	NE	SW	SW
1929	SW	SW	SW	SW	SW	S	SW
1930	NE	SW	SW	SW	NE	SW	E
Normal	SW	SW	SW	SW	SW-NE	SW	SW

Table 7.- Monthly mean wind velocity at Sandusky, Ohio, April to October for the years 1928, 1929, and 1930, and the normal. Velocities in miles per hour

Year	April	May	June	July	August	Sept.	Oct.	Mean Apr.-Oct.
1928	10.4	6.6	7.5	5.9	6.0	7.6	7.7	7.4
1929	10.3	8.0	6.9	6.6	6.2	6.4	8.9	7.6
1930	8.9	7.9	7.3	6.2	5.7	6.8	6.5	7.0
Normal	10.9	8.6	7.9	7.3	6.9	7.8	8.8	8.3

Water Temperature

Introduction

With the exception of the detailed data collected by Parmenter (1929) in Lake Erie, our knowledge of temperatures in the deeper parts of the Great Lakes is limited to a few occasional records, some of which are obviously erroneous. Coleman (1922) reviewed many of the early records. Wright (1931) cited other records, and called attention to the fact that bottom temperatures below 4° C. in summer have been found in all of the five Great Lakes except Lake Erie. A large number of surface temperatures are recorded by Horton and Grunsky (1927).

In the present investigation all temperature readings were taken with a Richter & Wiese reversing thermometer. The instrument used was graduated in degrees and tenths of degrees centigrade, and readings were made to the nearest 0.05 degree.

The temperature conditions in Western Lake Erie are extremely simple and are normally quite uniform over a large area. The simplicity and uniformity result from the nature of the basin; it is not only shallow, but it is unusually uniform in depth over large expanses. For that reason, the records of almost any station will be found typical of a large area surrounding it, although the records at different stations may vary in minor details. However, a record of temperatures at one station taken intermittently over a long period may not show the same characteristics as the record of another nearby station taken intermittently on different dates. This is true because a thermocline may be established and destroyed in a short time, and thus not appear on a record taken at one or two week intervals.

The record of Station 158 (Stone's Cove) has been selected for presentation because it is more complete than any other and because it appears to be typical of the offshore area. It is close to the shore of South Bass Island, but the water deepens so rapidly at that point that the temperature seems to be unaffected by the island's presence. Data from other stations will be given in order to make up the deficiencies in the record at Station 158 and to show conditions at special points in the lake.

Thermal Stratification

Western Lake Erie is characterized by almost total absence of thermal stratification. The record of Station 158 for 1929, given in Table 8 shows this fact very well. On only one of the 16 dates for which temperature data are available was there any evidence of stratification. The date was June 27, when there was a gradient of 1.25° C. in the stratum between 8 and 9 meters.

On this particular occasion the 9 meter reading was unusually near the bottom. Had the bottom reading been taken at 8.5 meters, the presence of the colder water might have escaped notice. It is entirely possible that similar thin strata of cold water escaped notice on other dates, when the bottom temperature was taken one meter above the bottom. But, obviously, little importance can be attached to strata of such thickness, especially when the temperature gradient is no greater than in the case cited. In the remaining fifteen series the top and bottom temperatures were identical on four occasions, and the maximum difference observed was 0.95° C.

That the almost complete absence of stratification at Station 158 was not a local peculiarity is shown by a summary of the temperature record at Station 8F (North Passage) as given in Table 9. Of the 12 series taken in 1929, only two show a marked temperature gradient: those of June 17 and June 24. On June 17 the change from surface to bottom was gradual and there was no thermocline as it is commonly defined, that is, a stratum in which the change is at least one degree centigrade per meter. On June 24 there was a thermocline between 8 and 10 meters, where there was a temperature difference of 3.45°. It is probable that stratification was quite general at this time, for on the following day a thermocline was found between 8 and 9 meters at Station 68 (Niagara Reef), and between 7 and 8 meters at Stations 75 (West Sister) and 134 (Middle Sister). In the three cases just mentioned, the gradient was less than 2° per meter.

Another period of stratification occurred earlier in the season, as indicated by a vertical series of readings taken at Station 60 (Gibraltar Island) on May 30. On that date the surface temperature was 21.75° and the bottom was 12.75°, or a change of 9.0° in 7 meters. There were two transition zones present, one in the upper 1.5 meters and the second in the stratum between 3 and 5 meters, each underlain by a stratum in which the gradient was less marked. Judging from temperatures taken at other stations before May 30, and from meteorological data for May 31 to June 3, when the next water temperatures were taken, the entire period of thermocline formation and destruction lasted only 6 days.

The temperature record at Station 158 for 1930 (Table 10) is almost as free from evidence of stratification as the record of 1929. On only two dates (May 6 and June 3) was there a temperature gradient great enough to be termed a thermocline. On May 6 it was located in the stratum between 7 and 8 meters, and the gradient was 1.4° for that one meter stratum. On June 3 there was a thermocline between 5 and 6 meters, but the gradient was only 1.0°. On the remaining twelve dates there were only insignificant differences between the surface and bottom.

Likewise, the record at Station 8F for 1930 shows only two examples of stratification (Table 11). On May 8 there was a thermocline with a gradient of 1.5° between 8 and 9 meters. On June 25 the thermocline was located between 10 and 11 meters, and the gradient was again 1.5°. The first of these two instances belongs to the same period of thermocline formation as the one

Table 8.- Temperatures at Station 158 (Stone's Cove) in 1929. Temperatures in degrees centigrade

Depth, meters	May 20	May 21	May 25	June 8	June 27	June 29	July 10	July 20	Aug. 7	Aug. 9	Aug. 16	Sept. 12[1]	Sept. 20	Sept. 25	Oct. 9	Oct. 22
0	11.6	12.75	14.95	15.8	21.7	21.5	22.6	21.9	21.95	22.6	21.5	20.6	17.8	17.45	14.2	12.7
8	11.55	11.8	14.70	----	21.1	21.25	----	----	----	----	----	----	----	16.8	----	12.7
8.5 to 9	----	----	----	15.7	19.85	----	22.4	21.9	21.65	21.75	21.25	20.6	17.8	----	14.05	----
Mean	11.6	12.3	14.80	15.75	[2]21.2	21.4	22.5	21.9	21.8	22.2	21.4	20.6	17.8	17.1	14.1	12.7

[1] Surface temperature on September 9 was 22.5

[2] By interpolation

Table 9 .- Summary of temperatures at Station 8F (North Passage) in 1929. Temperatures in degrees centigrade

Depth, meters	May 24	June 4	June 17	June 24	July 5	July 12	July 24	July 30	Aug. 9	Aug. 24	Sept. 13	Sept. 27
0	11.35	14.1	18.5	20.95	20.0	22.3	22.05	24.0	22.0	21.8	20.4	17.4
10 to 12	11.1	13.85	15.0	16.1	19.9	21.4	21.85	22.6	21.7	21.5	20.4	16.35
Mean	11.2	14.0	[1]16.7	[1]19.6	19.95	21.85	21.95	23.3	21.85	21.65	20.4	16.9

[1] Temperatures at certain intermediate depths not shown but used in determining mean

Table 10.- Temperatures at Station 158 (Stone's Cove) in 1930. Temperatures in degrees centigrade

Depth, meters	April 4	April 20	May 6	May 17	May 20	June 3	June 11	June 26	July 15	Aug. 1	Aug. 19	Sept. 5	Sept. 18	Oct. 1
0	2.9	6.95	12.05	14.1	14.75	17.95	16.5	22.6	22.6	26.0	22.7	22.85	21.6	16.9
2	---	---	---	---	[1]14.15	17.3	---	---	---	[1]25.1	---	---	[1]21.0	---
3	---	---	12.0	---	---	16.7	---	---	----	---	---	---	---	---
4	---	---	---	---	13.7	16.2	---	---	---	24.8	---	---	20.7	---
5	---	6.8	11.7	---	---	15.7	---	22.4	---	---	22.35	21.6	---	---
6	---	---	---	---	---	14.7	---	---	---	----	---	---	---	--
7	---	---	11.6	---	---	14.6	---	[1]22.1	---	----	---	---	---	---
8	---	---	[1]10.2	---	---	---	---	---	---	---	---	----	---	16.4
8.5 to 9	2.85	6.1	9.7	14.0	13.5	14.5	16.5	21.7	21.9	24.2	22.1	21.5	20.6	---
Mean	2.9	6.6	11.4	14.05	14.0	15.95	16.5	22.2	22.25	25.0	22.4	22.0	21.0	16.65

[1] Omitted in determining mean

Table 11 .- Summary of temperatures at Station 8F (North Passage) in 1930.
Temperatures in degrees centigrade

Depth, meters	May 8	May 23	June 12	June 25	July 12	Aug. 1	Aug. 19	Sept. 5	Sept. 24	Oct. 3
0	11.6	14.7	17.0	21.5	22.2	24.05	21.95	22.2	19.8	16.7
11	7.8	12.8	16.0	18.7	21.8	23.7	21.9	21.3	19.7	16.65
Mean	[1]10.4	[1]13.8	16.5	[1]20.7	22.0	23.9	21.9	21.8	19.75	16.7

[1] Temperatures at certain intermediate depths not shown but used in determining mean

at Station 158 on May 6. Reference to Table 10 will show that, if there was a thermocline at Station 158 on June 25, corresponding to the one at Station 8F, it was obliterated some time before the temperatures were taken on the following day.

The cases of thermal stratification in 1930 cited above indicate that there were at least three distinct periods of thermocline formation, the first in early May, the second in early June, and the third in late June. The record for Station 37A, given in Table 12, and partially in Fig. 7 shows the presence of thermoclines at corresponding times, and another in early August which is absent from the records of Stations 158 and 8F. It is of interest to note that the thermoclines of May 7 and June 5 were located nearer the surface than those at Station 158 on comparable dates. On May 7 it was found between 2 and 4 meters, and on June 5 between 4 and 6 meters, whereas at Station 158 it was found between 7 and 8 meters on May 6, and between 5 and 6 meters on June 3. The thermocline of June 20 at Station 37A was located at the same depth as the one at Station 8F on June 25, but it had a much steeper gradient than did the latter. That the thermoclines of June 5 and June 20 at Station 37A represent distinct periods of thermocline formation is indicated by the fact that the bottom temperature was higher on the latter date than on the former, and by the fact that at Stations 158 and 8F on June 11 and 12 respectively, there was no evidence of stratification.

An unusual condition existed at this station in early August. On August 9 the temperature was uniform in the upper 10 meters, but between 10 and 13 meters there was a gradient of 6.6°. The bottom temperature (18.2°) was lower than it had been on the three preceding dates. Three possible explanations for this condition may be suggested: (1) between July 18 and August 9, the water cooled to near 18° and subsequently warmed to near 25° in the upper 10 meters, (2) a layer of cold bottom water was forced westward from the deeper central basin as a result of disturbed hydrostatic equilbrium, (3) the bottom layer of water decreased in temperature about 3° through loss of heat to the cold bottom mud during a period of thermal stratification. The first explanation is not valid because the period in question was characterized by unusually high air temperatures. It is not possible to state definitely which of the other two explanations is the real one. The second seems improbable from the fact that on August 9 and on several preceding days the winds were light. If the western limit of the cold layer of the central basin lay only a short distance east of Station 37A, a strong wind would not be necessary to cause sufficient westward displacement, but since we have no data on this point, preference should be given to the third explanation. The minor cases of June 5 and July 9 (Fig. 7) might readily be explained by loss of heat to the mud, and with a more protracted period of stratification, it is not unlikely that the more pronounced reduction indicated in the present case could have taken place. On August 10 and 11 there were brisk winds and it is probable that the water was mixed from top to bottom.

The data which have been presented are considered typical of Western Lake Erie, although they have been taken from only a few stations. A review of the data shows clearly that thermal stratification is the exception rather

Table 12.- Temperatures at Station 37A (Kelleys Island) in 1930. Temperatures in degrees centigrade

Depth, meters	April 5	April 21	May 7	May 21	May 26	June 5	June 20	July 2	July 9	July 18	Aug. 9	Aug. 23	Sept. 19	Oct. 2
0	2.7	5.4	14.5	13.0	14.2	18.1	19.2	20.2	22.0	22.6	24.9	20.95	20.7	17.4
2	---	---	14.1	---	---	---	---	---	---	---	---	---	---	---
3	---	---	[1]11.6	---	---	17.9	---	---	---	---	---	---	----	---
4	---	---	9.9	---	---	[1]17.3	---	---	---	22.4	---	---	---	---
5	---	5.05	---	13.0	---	16.2	19.05	---	---	---	24.8	---	---	17.4
6	---	---	9.2	---	---	[1]14.8	---	---	21.7	---	---	---	---	---
7	---	---	---	---	---	14.4	---	---	---	---	---	---	---	---
8	---	---	8.8	---	---	---	---	---	21.0	22.0	---	---	---	---
9	---	---	---	---	---	14.2	---	---	20.3	---	---	---	---	----
10	---	---	7.8	12.6	---	---	19.0	---	20.0	---	24.8	---	----	----
11	---	---	---	---	---	14.0	15.7	---	---	---	23.4	---	---	---
12	---	---	---	---	---	---	14.9	---	----	---	19.5	---	---	---
13 to 13.5	2.7	5.0	6.9	12.15	14.0	13.5	14.8	20.1	19.0	21.1	18.2	20.95	20.7	16.9
Mean	2.7	5.15	10.2	12.7	14.1	15.5	[2]18.25	20.15	[2]21.0	22.0	[2]23.9	20.95	[3]20.7	17.2

[1] Omitted in determining mean

[2] By interpolation

[3] The temperature on September 6 was estimated to be 21.8° C, on the basis of records from a nearby station

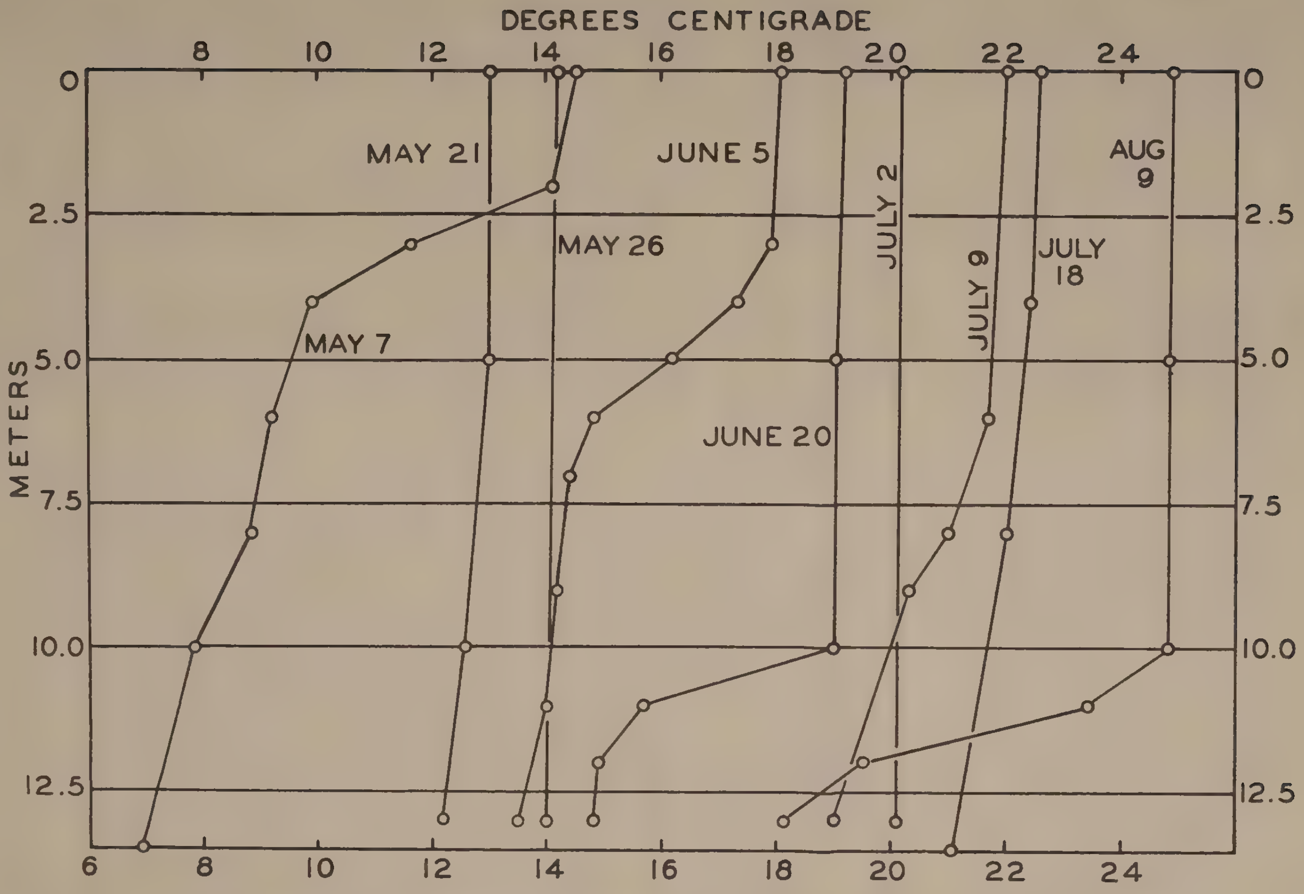

Fig. 7--Progressive change in temperature conditions at Station 37A over a period of three months in 1930. Data taken from Table 12.

than the rule. Usually the water is nearly uniform in temperature from surface to bottom. During a period of rising temperatures and gentle winds a thermocline may be established, to be destroyed in a few days and replaced by another at a higher temperature range. The available evidence indicates that there were two periods of thermal stratification in 1929 and three in 1930. At most of the stations where a thermocline was observed, it was small in vertical extent and in range of temperature. In two of the observed periods of stratification, the thermocline remained established long enough to bring about marked changes in the content of dissolved gases, as at Station 60 on May 30, 1929 and at Station 37A on August 5, 1930. But on the whole, thermal stratification may be regarded as a minor factor in the aquatic environment of Western Lake Erie. At the east end of the lake stratification persists throughout the summer period. For a discussion of the situation there, the reader may refer to Parmenter (1929).

Seasonal Changes in Temperature

The data collected during this investigation are incomplete in that they do not cover the months November to March, and in that they were taken too infrequently at any one station to show all of the changes which occurred. However, the records of several stations are complete enough to show the principal changes during the period April to October.

The mean temperature for each date on which temperatures were taken at Station 158 in 1929 is shown in Table 8 and Fig. 8. When the first readings were taken, on May 30, the mean temperature was 11.6°. Between May 20 and July 10 the rise was rapid, and the highest mean temperature for this station (22.5°) was attained on the latter date. During midsummer the record is somewhat atypical in that it fails to show a period of rising temperature in late July. This was noted on July 30 at Station 8F (Table 9) and at a number of other stations for which data are not presented. A study of all the available data indicates that the maximum temperature of the season occurred in late July, and that the high point of early September was about the same as that of early July. After mid-September the temperature declined rapidly at Station 158 and on October 22 it was nearly as low as on May 20.

At Station 8F (Table 9 and Fig. 9) only one peak, the one of late July, shows on the record. It may be seen that this station lagged behind Station 158 during the warming period of early summer and during the cooling period of early autumn. This more rapid warming and cooling of the water at Station 158 than at 8F is readily explained by the fact that the latter station is about three meters deeper than the former, and consequently there is a greater mass of water to be warmed and dooled. A similar difference in rapidity of warming and cooling may be found in comparing Station 158 with 8F for 1930 (Tables 10 and 11). If we compare Stations 158 and 37A for 1930 (Fig. 10), we find there was a distinct lag during the warming period at Station 37A, which is about 5 meters deeper than Station 158. However, during that part of the cooling period for which data are available, the lag was very slight.

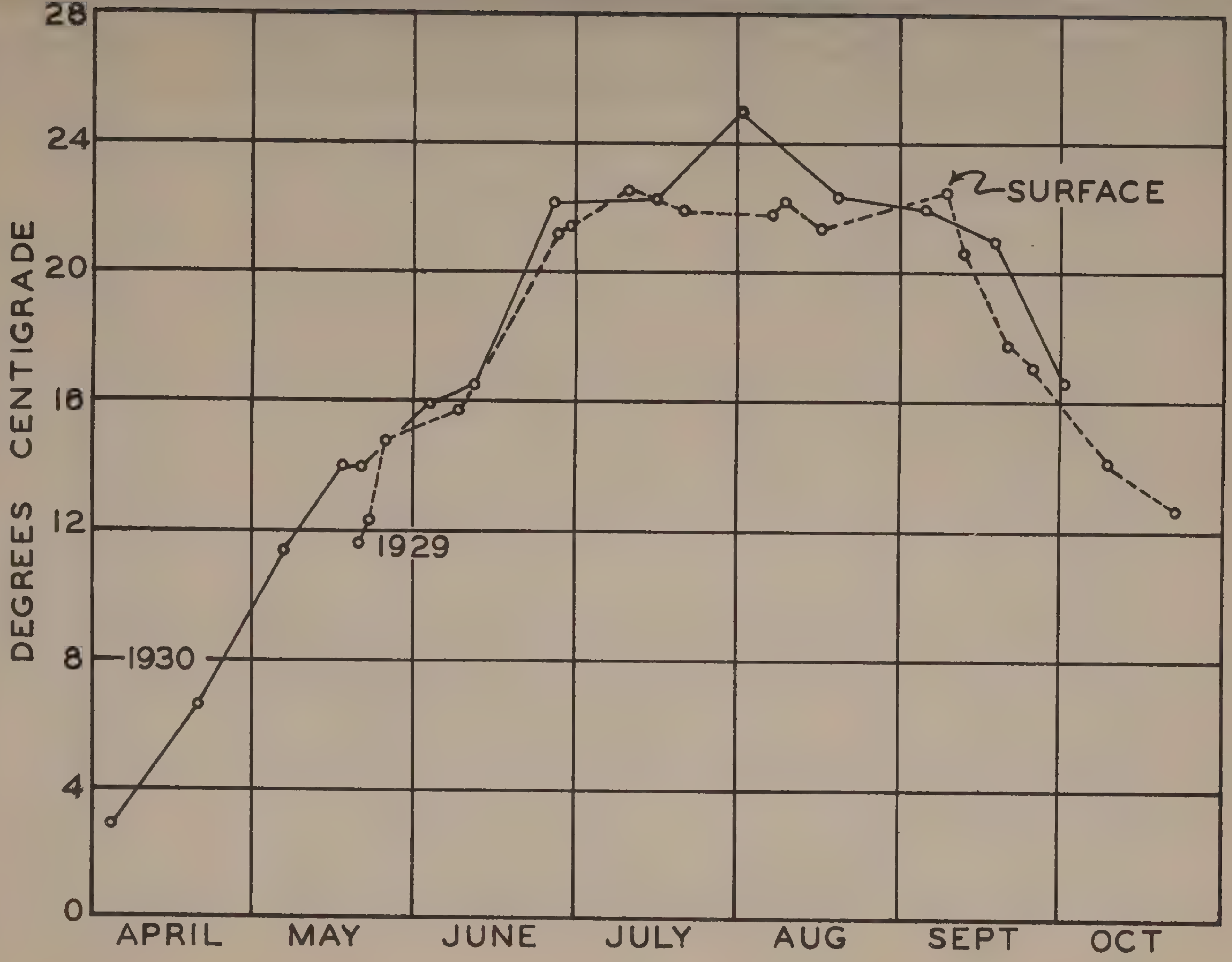

Fig. 8--Comparison of the mean water temperatures at Station 158 in 1929 and 1930. Data taken from Tables 8 and 10.

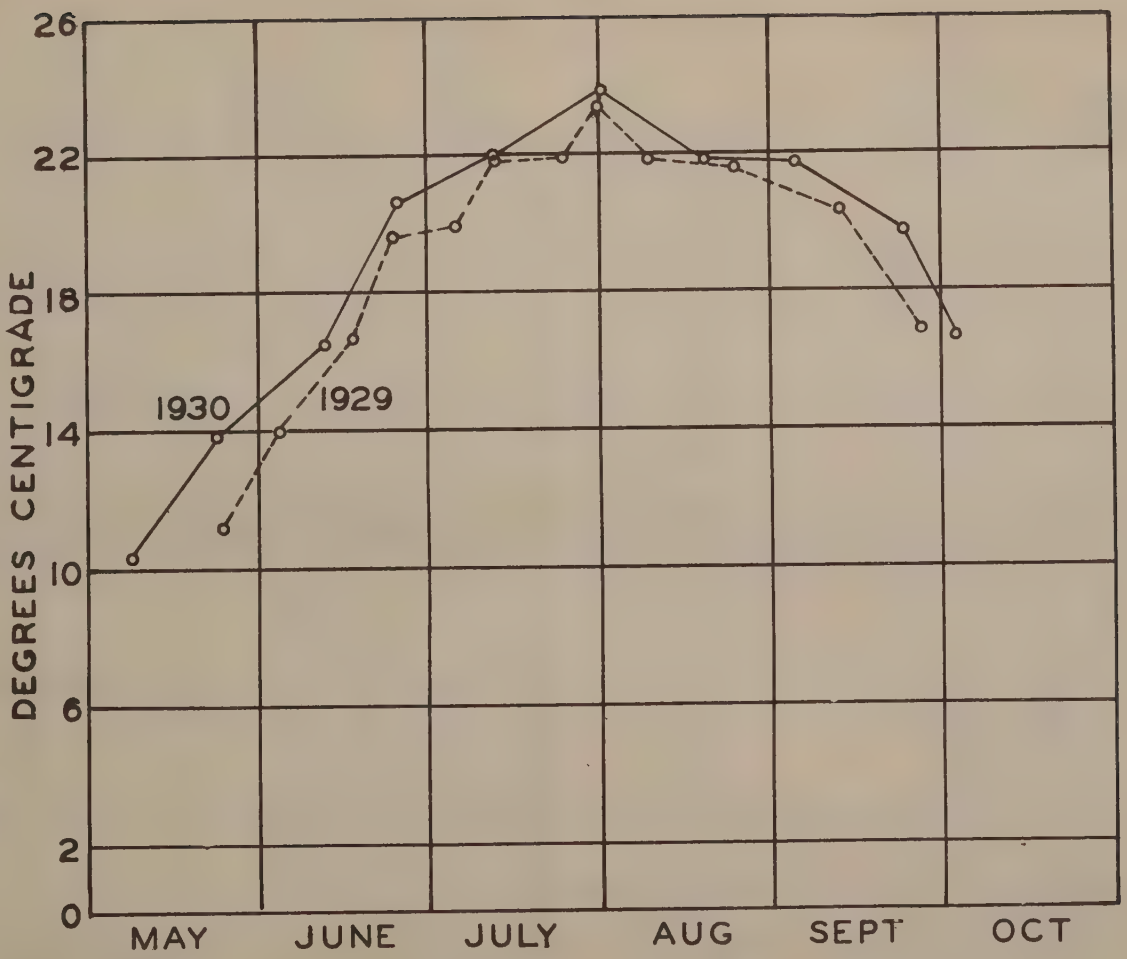

Fig. 9--Comparison of the mean water temperatures at Station 8 F in 1929 and 1930. Data taken from Tables 9 and 11.

In 1930 temperature readings were taken much earlier in the season than in 1929, but they were not continued so far into the autumn period. On April 4, when the first temperatures were taken at Station 158, the mean temperature was 2.9° (Table 10, Fig. 8). In the following weeks the temperature increased rapidly, and reached 22.2° on June 26, or somewhat earlier than in 1929. The highest point of the season (25.0°) was found on August 1, very close to the time of maximum for 1929 as indicated by the record at Station 8F. By August 19 the temperature had lowered to 22.4°, and by September 5 to 22.0°. In the latter part of September the temperature fell rapidly, and on October 1 it was about the same as on June 11. The records at Station 8F and 37A are similar to that at Station 158, except that they show lower temperatures for most of the comparable dates.

If we compare the records of temperature at Station 158 for 1929 and 1930, we find that the water was noticeably warmer in 1930 (Tables 8 and 10; Fig. 8). This fact is even more clearly shown in the records of Station 8F (Tables 9 and 11; Fig. 9). The explanation may be found in the records of air temperatures at Sandusky for those two years. Reference to Table 4 will show that, on the average, each of the months of May, June, July, August and September was warmer in 1930 than in 1929. April and October were warmer in 1929 than in 1930, but for April 1929, data on water temperatures are lacking, and the records of October 1930 were made very early in the month.

The stations located in shallow water at the mouths of small rivers showed a more rapid response to changes in air temperature than the stations in deeper water; they were warmer in periods of rising temperature and cooler in periods of falling temperature. The temperatures at Station 126 (Detroit River) were similar to those at other stations in the open water of the western part of Western Lake Erie. During 1929 temperatures were taken at Stations 126, and 117 (off Monroe), within a period of two hours on five dates. The mean of the five values was 19.65° at Station 126 and 20.6° at Station 117, or a difference of slightly less than 1.0°. A similar but smaller difference was noted between Stations 126 and 134 (Middle Sister) on four dates in the same year. The explanation for the small difference is probably that the water coming from Lake Huron is warmed considerably in passing through shallow Lake St. Clair before entering Detroit River. Maumee Bay was characterized by high temperatures during the summer period.

Transparency

Transparency was measured by means of a Secchi disc 20 centimeters in diameter, painted entirely white. Readings were always made on the shady side of the boat. The disc was lowered until it disappeared from view, then raised until it appeared, and the mean of the two readings recorded. Readings were made to the nearest one tenth meter.

The water of Western Lake Erie is characterized by low transparency. The highest reading taken during the two seasons of 1929 and 1930 was 4.8

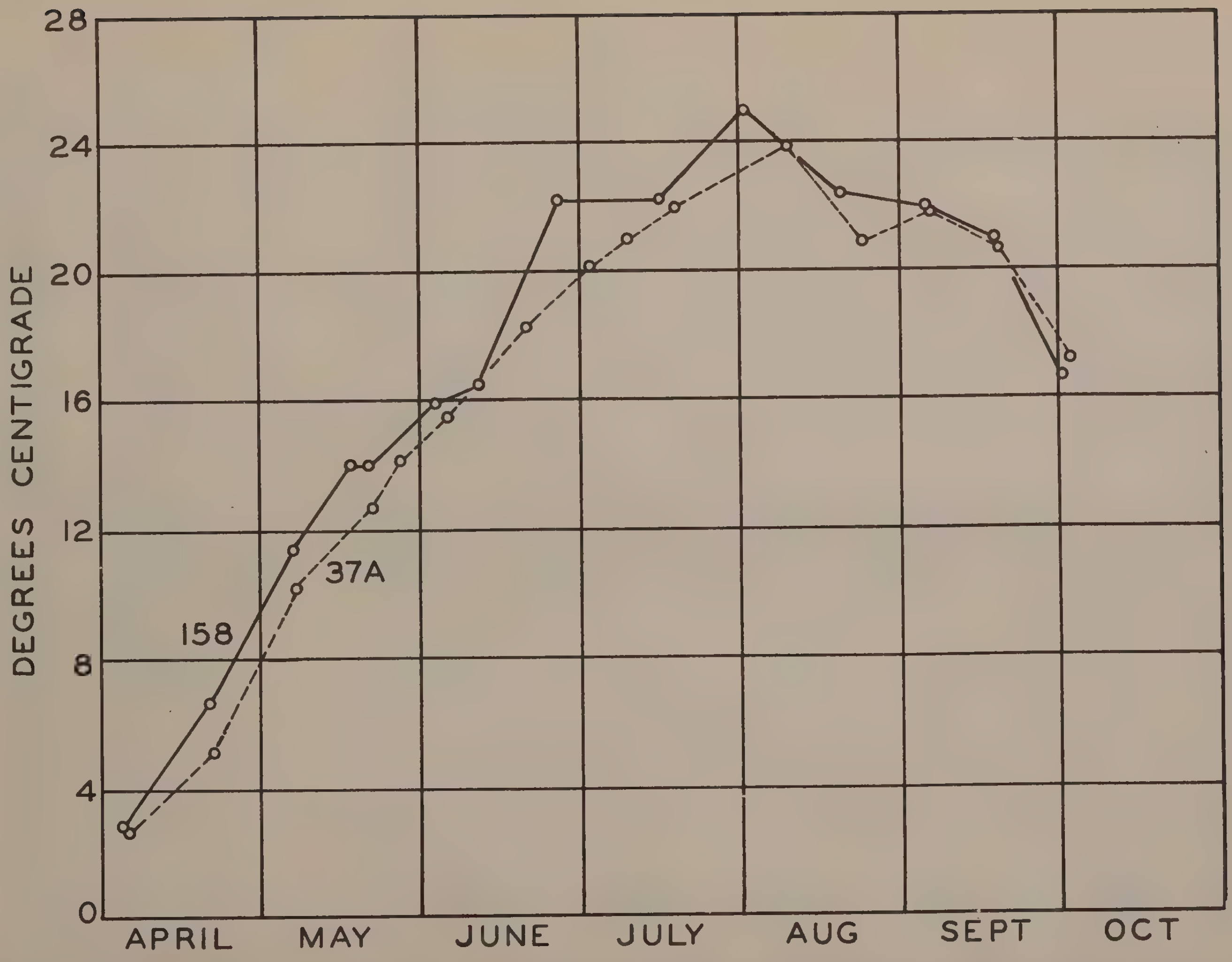

Fig. 10--Comparison of the mean water temperatures at Stations 158 and 37A, 1930. Data taken from Tables 10 and 12.

meters, observed at Station 134 (Middle Sister) on June 25, 1929. Only one other reading exceeded 4 meters; a reading of 4.5 meters at Station 8F (North Passage) on August 9, 1929. Transparencies exceeding 3 meters were uncommon in both years, and most of the readings taken during the summer periods were between 1 and 2 meters.

In general, stations with highest transparency were those far from rivers or other sources of sediment. There was a decided seasonal change in transparency. The lowest observations were made in spring, the highest in summer; in fall transparency was lower than in summer but higher than in spring.

The water in the eastern part of the lake has a much higher transparency than in the western part. Parmenter (1929) reported a maximum reading of 10.5 meters and a minimum of 2 meters for 1928. The average was between 5 and 8 meters.

A CHEMICAL STUDY OF WESTERN LAKE ERIE

Introduction

Previous Investigations in the Great Lakes

The Great Lakes have served as a source of water supply for many cities over a long period of time. It is only natural, then, that the waters of the lakes have been subjected to detailed chemical analysis at different times and places to determine their suitability for domestic and industrial uses. Many reports of chemical studies have appeared in well-known publications which are readily obtainable; others have appeared in special publications which are less accessible to the general public. The reports which have come to the attention of the writer will be noted briefly here, but in all probability the list is imcomplete.

Our knowledge of the mineral constituents of the lake waters is based principally on the investigations of Dole (1909). Dole made eleven analyses of the water of each of the five Great Lakes near their mouths. The work was done over a period of a year in 1906 and 1907. Table 13 presents the data in summarized form. They are given here as a convenience to those who may be interested, and will not be discussed.

Dole's report contains data on a number of the tributaries of the Great Lakes. Additional analyses of some of the lake waters and tributary streams are given by Bartow and Birdsall (1911), Clarke (1924), Foulk (1925), Detroit Department of Water Supply (1930), and McNamee (1930).

In addition to these mineral analyses, a number of so-called sanitary analyses have been made. Reports of such investigations in Lake Superior and Huron, if made, apparently have not been published, although Mason (1917) gives the results of one set of analyses from the open water of Lake Superior. Van Oosten (1929) discussed the pollution of Saginaw Bay, Lake

Table 13.- Mean composition of the water of the Great Lakes. Data from Dole (1909)

(parts per million)

Item	Lake				
	Superior	Huron	Michigan	Erie	Ontario (St. Lawrence R.)
Silica (SiO_2)	7.4	12.0	10.0	5.9	6.6
Iron (Fe)	0.06	0.04	0.04	0.07	0.05
Calcium (Ca)	13.0	24.0	26.0	31.0	31.0
Magnesium (Mg)	3.1	7.0	8.2	7.6	7.2
Sodium (Na) and Potassium (K)	3.2	4.4	4.7	6.5	6.3
Carbonate radicle (CO_3)	0.0	1.8	2.9	3.1	2.9
Bicarbonate radicle (HCO_3)	56.0	100.0	112.0	114.0	116.0
Sulphate radicle (SO_4)	2.1	6.2	7.2	13.0	12.0
Nitrate radicle (NO_3)	0.5	0.4	0.3	0.3	0.3
Chlorine (Cl)	1.1	2.6	2.7	8.7	7.7
Total solids	60.0	108.0	118.0	133.0	134.0

Huron, by dichlorobenzol, and its effect on the fishes of the bay. Lake Michigan has been studied in some detail, particularly in the vicinity of Chicago. Perhpas the most complete study of this kind was reported for the lake water at Chicago by Palmer (1903). Somehwat less complete data for other points in the southern part of the lake are given by Bartow (1909 and 1909a) and Barnard and Brewster (1909). More recent investigations in this area, such as those reported by the Chicago Sanitary District, Engineering Board of Review (1925a) and Crohurst and Veldee (1927), have been restricted to determinations of dissolved oxygen and biochemical oxygen demand. There have been no chemical studies of Green Bay, but the Wisconsin State Board of Health (1927) has reported on an extensive investigation of the lower part of Fox River to the point where it empties into the bay. In their study of the forms of nitrogen in lake waters, Domogalla and his associates made a few analyses of the water of Lake Michigan. The data will be found in the following papers listed in the bibliography: Domogalla, Juday, and Peterson (1925), Peterson, Fred, and Domogalla (1925), and Domogalla, Fred, and Peterson (1926).

Only a few sanitary analyses for Lake Ontario have been reported. Goodwin (1892) made a brief study of the water supply of Kingston, Ontario, and Whipple (1913) analysed a few samples from the lake near the mouth of Genesee River. A recent report by Faigenbaum (1932) contains a large number of data on dissolved oxygen, carbon dioxide, and pH of Black River Bay and and of tributaries to this bay and St. Lawrence River.

Lake Erie has been studied more extensively than the other lakes of the system. The Ohio State Board of Health (1899) made a large number of sanitary analyses in Sandusky and Maumee Rivers, and later (1902) reported on the water supplies of several cities along the lake shore. The Detroit Board of Health (1902) published the results of a study of Detroit River water over a period of a year. A two-year investigation of the lake water at Cleveland was reported by Jackson (1912). Donaldson and Furman (1927) studies the phenol wastes in Maumee River and in the lake at the extreme west end. Reports on the mineral constituents by Dole (1909), Clarke (1924), Foulk (1925), Detroit Department of Water Supply (1930), and McNamee (1930) have been mentioned previously. The last two reports concern some of the tributaries at the west end of the lake.

In recent years there have been a number of studies of the chemistry of the lake with a view of determining its suitability for aquatic organisms, particularly fishes. In 1920 and 1921 Professor Jacob E. Reighard supervised a detailed pollutional study of the lower part of River Raisin. The results of this study have not been published, but Professor Reighard has generously placed his manuscript at the writer's disposal. Certain of the data on dissolved oxygen in the river and in Lake Erie nearby will be introduced in later pages of this report. Osburn (1926 and 1926a) reported the oxygen content and pH at a number of points at the west end of the lake and along the south shore. In 1928 the lake east of Long Point was studied in some detail by several co-operating agencies. Wagner (1929) reported on the waters along the south shore and on a number of tributary streams in that region. Williams (1929) and Burkholder (1929) discussed the chemistry of the open lake with respect to nitrogen, oxygen, carbon dioxide, and pH. In 1929 the investigation was extended to cover all of the lake east of Western Lake Erie, but determinations of nitrogen were discontinued. The results of this study have not been published. The Michigan Stream Control Commission has recently made a study of the oxygen content of Huron and Raisin Rivers, as well as of Black River for some distance above its confluence with St. Clair River at Port Huron, Michigan. The data have not been published, but have been made available to the writer in the form of blue-printed charts.

No attempt will be made to review here the results obtained in the chemical studies of Lake Erie and its tributaries, but in the body of this report those which have a bearing on the problem will be discussed, and, in some cases, compared with those obtained in the present investigation.

Scope and Methods

This report is based on a large number of analyses of the water of Western Lake Erie made in the years 1928, 1929, and 1930. Analyses for dissolved oxygen, free and fixed carbon dioxide, and hydrogen ion concentration were made in all three years. In addition the program in 1930 was expanded to include determinations of chlorine as chloride, and nitrogen as free and albuminoid ammonia, nitrite, and nitrate. With the exception of a few samples taken in February, 1930, the samples were taken within the period April to October, inclusive. Samples for chemical analyses were taken with a Kemmerer-Foerst water bottle similar to the one described by Birge (1922). In 1928 the analyses were made on the boat, but in 1929 and 1930 this work was done in the laboratory at Put-in-Bay. The few samples taken in February 1930 were analysed in a temporary laboratory at Monroe, Michigan.

In 1928 dissolved oxygen was determined by the Winkler method as modified by Rideal and Stewart (American Public Health Association, 1925). In 1929 and 1930 the original Winkler method was used on water from the Island Section, while the Rideal-Stewart modification was retained for samples near the rivers. Numerous parallel tests showed that the two methods gave concordant results in the Island Section, but not in the polluted areas. All chemical values in this paper are reported in parts per million (milligrams per liter), except those for percentage of oxygen saturation and hydrogen ion concentration. Percentage of saturation was computed according to the table on page 62 of the reference work noted above, which is generally known as "Standard Methods".

Free carbon dioxide was determined by the Seyler method (Birge and Juday 1911) in 1928, 1929, and until June 14, 1930. At that time the procedure recommended in Standard Methods was adopted. In the tables of this paper, the presence of free carbon dioxide is indicated by a plus sign, and a deficiency of the gas by a minus sign. Figures following a minus sign show the amount of carbon dioxide which would have to be added to change all of the calcium carbonate to calcium bicarbonate and render the water neutral to phenolphthalein.

Fixed carbon dioxide was determined according to the recommendations in Standard Methods, and the results are recorded as methyl orange alkalinity in terms of calcium carbonate. Hydrogen ion concentration was determined, in terms of pH units, by the use of La Motte color standards and block comparator.

All four forms of nitrogen were determined by the methods given in Standard Methods. It should be pointed out here that analysis for nitrogen as albuminoid ammonia does not yield all of the nitrogen in organic form, but only that of the relatively unstable compounds which are readily acted upon by alkaline potassium permanganate. Total organic nitrogen cannot be calculated from the albuminoid nitrogen because the stable and unstable compounds are not always present in the same relative proportions. The figures given by Leighton (1907, Table 63) on the water of the Chicago drainage canal and Illinois River indicate that albuminoid nitrogen was, on the average, one half of the total organic nitrogen. It is not improbable that a similar relation exists in the water of Lake Erie.

Data and Discussion

Island Section

Oxygen, carbon dioxide, and hydrogen-ion concentration

Season of 1928

Investigation of the chemistry of the water in 1928 was carried on in connection with the study of larval fish. Samples were taken at a large number of stations but they were not visited frequently enough to show the seasonal changes completely. Moreover, most of the determinations were made on the deck of the Investigator, often under the most unfavorable conditions for such work. The colorometric determination of small amounts of free carbon dioxide is difficult in the laboratory, and it would be surprising if accurate results were obtained on the deck of a small boat. Some of the data on free carbon dioxide given in Table 25 appear to be erroneous since they show no relationship to the dissolved oxygen and pH, which, in most cases, are in close agreement.

Only a small part of the data will be presented here. The data from Stations 18, 59A, and 76 are given in Table 14. The location of Stations 18 and 59A may be seen in Fig. 1. Station 76 is located a short distance south of Green Island, which is off the west shore of South Bass Island. Temperatures were taken with a Fahrenheit thermometer which was read to the nearest degree. These figures were changed to the centigrade scale, and recorded in degrees and half degrees to avoid fictitious accuracy.

The data will be discussed briefly as a group. Dissolved oxygen in the surface stratum was high for all samples. In four instances there was supersaturation, and the per cent of saturation never fell below 86. Most of the bottom samples showed some reduction in oxygen, but in no case did it fall below 62 per cent, so that the depletion was never serious.

Table 14.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at surface and bottom of Stations 18, 59A, and 76 in 1928. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Station	Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
				parts per million		per cent saturation							
		S	B	S	B	S	B	S	B	S	B	S	B
18	June 1	16.5	16	10.2	10.4	104	105	-3.6	-3.0	90	93	8.3	8.3
	June 9	16	16	9.8	7.6	98	76	-2.0	-2.0	90	88	8.3	8.2
	July 10	22	18.5	7.6	6.1	86	65	-1.4	+1.2	95	95	7.9	7.6
	September 26	16	16	9.1	9.1	91	91	-3.0	-3.0	87	87	8.3	8.3
59A	June 6	15.5	15.5	10.5	9.8	104	98	-2.0	-2.0	92	92	8.3	8.1
	June 21	20	18.5	9.4	8.2	103	87	-2.0	-1.0	95	95	8.1	7.7
	July 9	23	18	8.0	5.9	92	62	-2.0	+0.5	86	86	8.1	7.6
	August 17	25.5	24.5	8.9	6.1	107	72	-5.9	-2.0	93	93	8.5	8.1
	October 2	15	14.5	9.6	8.9	96	87	-2.4	-2.4	92	90	8.4	8.3
76	June 11	16.5	16	9.3	9.2	94	92	-2.0	-2.0	95	92	7.9	7.9
	June 25	19.5	19.5	8.3	7.3	90	79	-4.0	-1.0	88	89	8.1	7.7
	August 9	--	--	7.9	5.7	--	--	-5.0	-1.0	92	92	8.4	7.7
	October 1	14	14	9.2	9.1	89	88	-3.0	-3.0	86	86	8.3	8.3

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The dates on which one or both of the determinations of free carbon dioxide appear to be erroneous are as follows: July 10 at Station 18: June 21 and July 9 at Station 59A; June 11 and 25, and August 9 at Station 76. The questionable samples show too great a deficiency or too small an excess of carbon dioxide for the corresponding pH readings and oxygen content. If the remaining samples are accurate, they show that the water was commonly deficient in free carbon dioxide. The pH values of the surface water tend to confirm this finding; only two of the 13 determinations were below pH 8.0, and the lowest was pH 7.9. Eight were pH 8.3 or more. Only seven of the bottom readings were 8.0 or above, and two were as low as 7.6. The low readings (7.6-7.7) were correlated with partial depletion of oxygen in the lower water. Methyl orange alkalinity (in terms of calcium carbonate) ranged from 86 to 95 parts per million: 17 of the 26 samples were above 90.

Certain general conclusions might be drawn from a study of the data, but it seems advisable to present the more complete data of 1929 and 1930 before attempting to draw the conclusions.

Season of 1929

In 1929 chemical samples were taken at eight stations in the Island Section as follows: 18, 37A, 59A, 82, 158, 68, 75, and 8F. The location of these stations may be seen in Fig. 1. Most complete data were obtained at Stations 37A, 158, and 8F, and since conditions were found to be quite uniform over the entire area, only these stations will be considered in detail.

Station 37A. Samples were taken at this station on nine dates in the period from late May to mid-October. It is recognized, of course, that samples were not taken frequently enough to detect all of the changes in chemical conditions which took place during the season, but it is believed that the major trends are shown by the data. Samples were usually taken at surface and bottom; on two occasions only surface samples were taken. The data are given in Table 15 and Fig. 11 is a graphic representation of the data from the surface.

The mean depth at this station was 14.2 meters. On every date for which data are available, the top and bottom temperatures were very nearly the same, indicating that the water was frequently mixed from top to bottom. For that reason only minor differences in chemical conditions between surface and bottom were noted. Oxygen content of the surface water varied from 10.5 to 7.8 parts per million. The water was never completely saturated but was more than 90 per cent saturated on every date but one. Oxygen was most abundant at the beginning and end of the season, when the temperature was low and solubility of the gas high. The lowest point was reached in early July, but since this was not the time of highest temperature of the water, some factor other than reduced solubility must have been involved. This is clear from the deep notch in the curve of saturation, which reached the low point of 84 per cent. The most probable explanation is that the oxygen was being used rapidly in decompo-

Table 15.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at surface and bottom of Station 37A, 1929. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date 1929	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
May 23	11.55	11.3	10.5	--	96	--	+0.8	--	93	--	7.8	--
June 11	17.05	14.9	9.5	9.4	98	92	-0.5	0.0	91	93	8.1	7.9
June 19	18.45	--	9.3	8.7	98	--	-2.0	-0.5	93	93	8.1	7.9
July 1	19.55	19.15	7.8	--	84	--	0.0	--	98	--	7.9	--
July 8	20.5	19.3	8.4	8.0	92	86	0.0	0.0	95	98	7.9	7.9
July 25	22.1	21.8	8.1	7.6	92	86	-2.3	-1.9	98	93	8.1	8.0
August 12	22.5	21.8	8.2	7.8	94	88	-0.5	+1.5	95	98	8.1	7.9
September 24	17.7	16.8	9.5	8.8	99	90	-1.3	-0.4	91	95	8.1	8.1
October 14	13.0	13.0	9.6	9.6	91	91	0.0	0.0	89	89	8.0	8.0

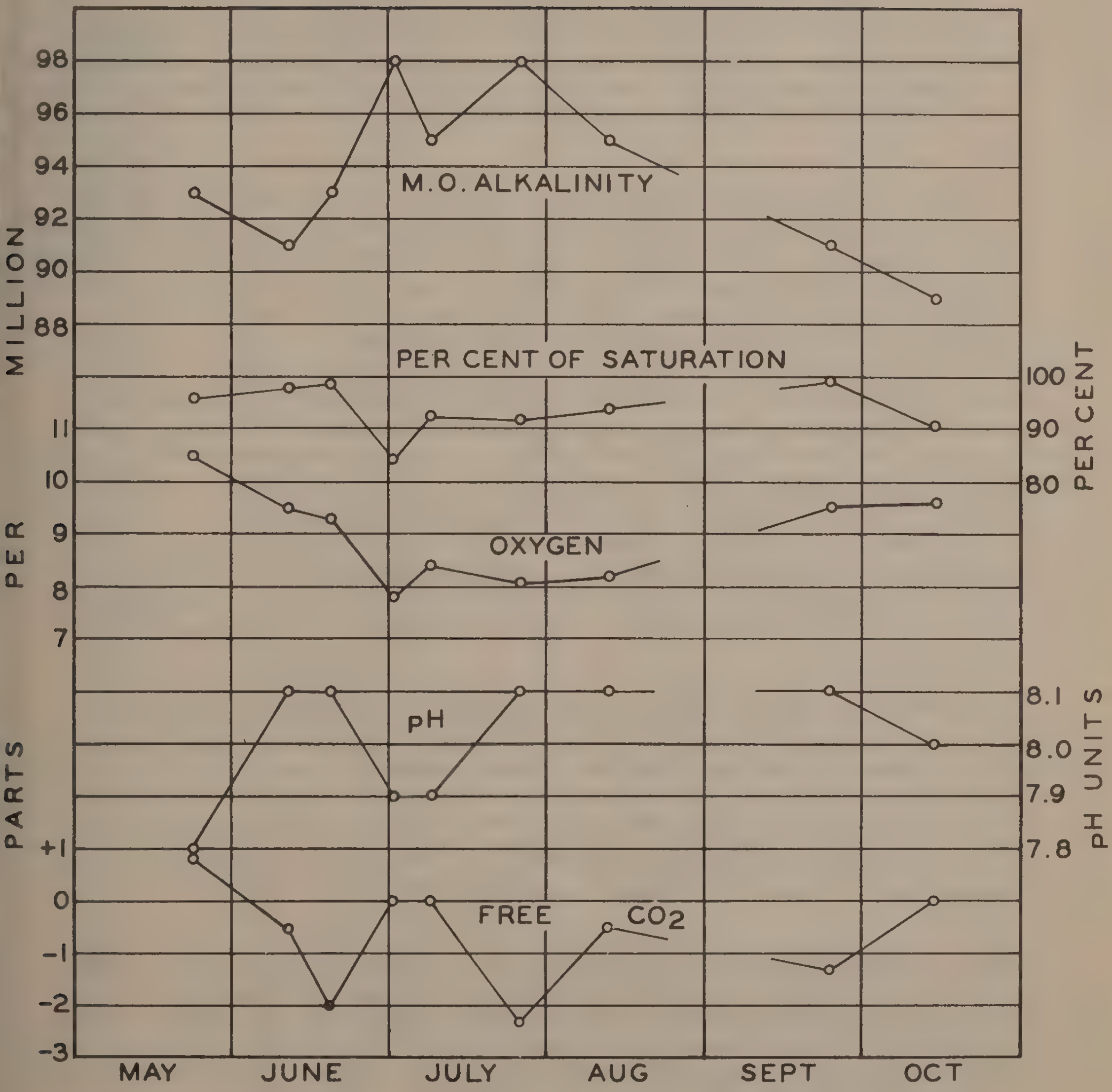

Fig. 11--Dissolved oxygen, free carbon dioxide, methyl orange alkalinity, and pH of the surface water at Station 37A, 1929. Data taken from Table 15.

sition of the spring crop of phytoplankton. The diatoms were very abundant in early June but declined in late June and reached the low point for the season on July 1. (Fig. 13). The dead cells would, of course, take a considerable amount of oxygen from the water during the process of decay. Recovery was rapid, for on July 8 the water was 92 per cent saturated, but there was little change observed on the two following dates. There were few phytoplankton organisms at this time, hence little photosynthetic activity. Unfortunately no samples were taken in early September. In late Septmeber, when algae were again abundant, the water was 99 per cent saturated, but on October 14 the algae were declining at Station 37A and oxygen was reduced to 91 percent of saturation. On every date but one when samples were taken near the bottom, the bottom water held less oxygen than the surface. The greatest observed difference was 0.7 part per million and it is doubtful whether depletion ever reached a point where it would be dangerous to organisms living at the bottom.

An excess of free carbon dioxide was found at the surface on only one occasion, May 23, when there was an excess of 0.8 part per million. In June there was a deficiency of the gas as a result of removal of part of the half-bound carbon dioxide by algae. This deficiency was removed by July 1, at which time the oxygen was at its lowest point. On the next two dates the curves for carbon dioxide and oxygen are not in complete agreement. When the oxygen increased between July 1 and 8 there was no corresponding change in the carbon dioxide. In late July the carbon dioxide deficit reached 2.3 parts per million but the oxygen content remained almost unchanged. The single sample taken in August showed only a slight deficit. It was somewhat greater in late September, when the phytoplankton was abundant, but on October 14 the water was neutral to phenolphthalein. The differences observed between surface and bottom samples were not of great magnitude. On August 12 the bottom water held an excess of 1.5 parts per million when the surface water had a deficit of 0.5 part per million; and on June 19 there was a difference of 1.5 parts per million between the two depths. On the remaining dates little or no difference was found.

The curve of pH values shows close relationship to the curve of free carbon dioxide; only in the sample taken in August was there failure to respond to a change in carbon dioxide. Exact agreement should not be expected because other factors than free carbon dioxide (particularly carbonates) affect pH. The pH ranged from 7.8 to 8.1. On three occasions when surface and bottom samples were taken, they were the same; on three other occasions the surface was pH 8.1 and the bottom pH 7.9; once the surface was pH 8.1 and the bottom pH 8.0.

Methyl orange alkalinity ranged from 89 to 98 parts per million. The highest values were observed during July and the lowest in October. The greatest difference between surface and bottom samples was 5 parts per million, on July 25. In this case the larger amount was at the surface; in other cases where there was a difference, the large amount was at the bottom.

Table 16.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 158, 1929. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
May 21	12.75	11.8	9.6	--	90	--	+1.2	--	91	--	7.8	--
June 8	15.8	15.7	8.9	--	89	--	-1.0	--	93	--	8.1	--
June 29	20.85	20.7	7.9	7.8	88	86	-0.5	-0.5	93	93	8.1	8.1
July 10	22.6	22.4	8.3	--	95	--	-2.0	--	93	--	--	--
July 20	21.9	21.9	8.3	8.2	94	93	-2.5	-2.6	93	91	8.2	8.2
August 9	22.6	21.75	8.7	--	100	--	-0.8	--	98	--	8.1	--
August 16	21.5	21.25	8.4	8.2	94	92	-1.0	-1.0	95	95	8.1	8.0
September 12	20.6	20.6	8.8	8.8	97	97	-2.0	-2.0	95	95	8.1	8.1
September 30	17.3	17.25	9.4	--	97	--	-0.9	--	89	--	8.1	--
October 22	12.7	12.7	10.0	10.0	94	94	0.0	0.0	95	95	8.0	8.0

Station 158. The mean depth at this station was 9.6 meters. Samples were taken here on 10 dates; on five of these dates only surface samples were taken. The data are shown in Table 16. Only minor differences were found between the surface and bottom samples when both were taken. On dates when both were not taken, the largest difference in temperature was 0.95° C., hence, it is probable that the chemical conditions were nearly uniform from top to bottom during most of the season. Conditions here were essentially like those at Station 37A, but differed from them in details, which might be expected from the fact that the two stations were not visited on the same dates. In the discussion which follows, the notable differences will be pointed out.

Oxygen content of the surface water ranged from 7.9 to 10.0 parts per million. The smallest amount was found on June 29, that is, at about the same time as the marked decrease in oxygen at Station 37A. The decrease at Station 158 was less outstanding than at Station 37A because the oxygen content on the preceding and following dates was rather low. Contrary to the situation at Station 37A, oxygen approached nearest saturation in August. In other respects the conditions at the two stations were similar. At no time was there depletion of oxygen to the extent that it would be unfavorable to organisms in the lake. The smallest amount present in the lower water was 7.8 parts per million, which was 86 per cent saturated.

An excess of free carbon dioxide was found only on May 21; on every other date except October 22 there was a deficiency. The amount ranged from +1.2 to -2.6 parts per million. Seasonal changes in free carbon dioxide were similar to those at Station 37A. The principal difference is seen in the changes in June; these were less pronounced at Station 158 than at Station 37A, as was the case with oxygen.

The pH values ranged from 7.8 to 8.2. The seasonal changes agreed, in general, with those for free carbon dioxide. They differed from those at Station 37A in the absence of a decrease in pH at the time of lowest oxygen content. This difference might be expected from the less pronounced changes in free carbon dioxide at Station 158. Another minor difference was that the pH rose 0.1 unit higher at Station 158 than at Station 37A.

Methyl orange alkalinity ranged from 89 to 98 parts per million, the same range which was observed at Station 37A. The largest amount was found in early August and the smallest in late September. Only minor differences were noted between top and bottom samples.

Station 8F. The mean depth at this station was 12.1 meters. Table 17 shows the data obtained here on eight dates in 1929. On three of these dates samples were taken only at the surface, but in each case the top and bottom temperatures were so nearly the same that it is reasonable to assume that chemical conditions were nearly the same also. The data need not be discussed in detail because they do not differ in important ways from those at Stations 37A and 158. On two dates there were rather marked differences between surface and bottom samples due to temporary stagnation of the lower water, but depletion of

Table 17.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 8F, 1929. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
May 24	11.35	11.1	10.2	10.2	93	92	+0.8	+0.8	89	89	7.8	7.8
June 4	14.1	13.85	9.5	--	92	--	-1.0	--	89	--	7.9	--
June 11	18.5	15.0	9.4	8.7	100	86	0.0	+1.0	89	89	7.9	7.8
July 5	20.0	19.9	8.6	--	94	--	+1.0	--	93	--	7.9	--
July 24	22.05	21.85	8.7	8.3	98	94	-0.5	-0.5	91	86	8.1	8.1
August 9	22.0	21.7	8.5	--	96	--	-0.8	--	86	--	8.1	--
September 13	20.4	20.4	8.8	8.7	97	96	-1.0	-1.0	98	98	8.1	8.1
September 27	17.4	16.35	10.1	8.7	105	88	-1.3	+1.5	86	86	8.1	7.9

oxygen never went below 86 percent of saturation. Loss of oxygen in the upper water, which was noted at the other stations coincident with the decline of the spring crop of plankton, was less noticeable here. The sample of early July was taken on July 5, and judging from the data at Stations 37A and 158, this was after the time of maximum withdrawal of oxygen. On September 27, the surface water was supersaturated with oxygen. In late June - early July the pH remained constant at the surface in spite of a reduction of the deficit of free carbon dioxide. There was an excess of free carbon dioxide at the surface on two dates, and the carbon dioxide deficit was less marked than at the other stations. Methyl orange alkalinity ranged from 86 to 98 parts per million and there was no evidence of seasonal trend.

Station 60. The data which have been presented show such uniform conditions at the surface and bottom that it will be of interest to note an unusual condition which existed in the last few days of May. May 27, 28, 29 and 30 were very warm cloudless days and there was almost no wind. Owing to the fact that repairs were being made to the motor boat, it was not possible to take samples at any of the regular stations, but on May 30 a row boat was used to get samples at Station 60, which is located in the channel between Middle and South Bass. There was a temperature gradient of 9° C. between the surface and 7 meters; the surface was 21.75° and 7 meters was 12.75°. The oxygen content at the surface was 11.8 parts per million and at 7 meters, 9.2 parts per million, representing 133 and 87 per cent saturation respectively. At the surface there was a free carbon dioxide deficit of 3.0 parts per million and at the bottom an excess of 1.0 part per million. At the surface the pH was 8.4 and at the bottom it was 7.8. These data show clearly the influence of increased temperature and sunlight on photo-synthetic activity of the plankton algae. Without doubt, conditions similar to those at Station 60 existed at other stations in the Island Section. On June 1 a brisk wind mixed the water from top to bottom.

Season of 1930

The data obtained in 1930 are more complete than those obtained in 1929 because a longer period of time was covered and because samples were taken at more regular intervals. As in the discussion of the season of 1929, only the data from Stations 37A, 158, and 8F will be considered in detail.

Station 37A. Samples were taken at this station on 13 dates during a period from early April to early October. The data (Table 18) are complete except for the lack of temperatures on August 5 and September 6, and free carbon dioxide on October 2.

At Station 59A (about 7 miles from Station 37A) on August 9, there was only 0.78 part per million of oxygen at the bottom, representing 8.6 per cent of saturation. This is the only instance of almost complete exhaustion of oxygen which was found in three seasons of investigation in the Island Section. Judging by the temperature data of Station 59A, the layer of water low in oxygen did not exceed 3 meters in depth. Accompanying the oxygen depletion, there was an excess of 7.3 parts per million of free carbon dioxide. This pH was 7.3. Since there was a marked temperature gradient at Station 37A on August 9, it is reasonable to suppose that the partial depletion of oxygen noted on August 5 had become more pronounced by August 9, perhaps as much so as at Station 59A on the same date. It is probable that the water was mixed completely on August 10 and 11 because the winds were rather brisk on those two dates.

Free carbon dioxide at the surface of Station 37A ranged from +3.0 to -2.2 parts per million. In the period April-July there was an excess of the gas on six of the eight dates. In August and September the samples showed a deficiency of carbon dioxide. Judging by the pH on October 2, there was a deficiency on that date also. At the bottom there was an excess on all dates until August 23; on that date and thereafter there was a deficiency. On September 6 and 19, the deficit at the bottom was greater than at the surface. The largest amount of free carbon dioxide at the bottom was +5.7 parts per million, on June 20. A possible relationship with the phytoplankton is seen in the rather large excess of the gas at the surface on July 2, following the decline of plankton. Also the greatest deficiency of the gas was observed on September 19, when plankton was abundant.

Dissolved oxygen in the surface water ranged from 8.1 to 12.6 parts per million, and the water was never less than 89 per cent saturated. In one case it was supersaturated. There is little or no evidence of a relationship between the amount of oxygen and the abundance of phytoplankton. On May 7, before the plankton has increased greatly,(Fig.14)the surface water was

Table 18.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 37A, 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
April 5	2.7	2.7	12.6	12.5	93	92	+1.4	+1.4	90	90	7.8	7.8
April 21	5.4	5.0	11.7	11.7	92	91	+1.9	+1.9	92	94	7.8	7.8
May 7	14.5	6.9	11.4	11.2	111	92	-0.9	+1.4	89	97	8.1	7.9
May 21	13.0	12.15	9.4	9.3	89	86	+1.4	+1.9	90	91	8.0	8.0
June 5	18.1	13.5	8.5	8.1	89	77	0.0	+1.9	90	95	8.2	7.9
June 20	19.2	14.8	8.9	7.5	96	74	+1.3	+5.7	96	97	7.9	7.6
July 2	20.2	20.1	8.4	8.4	92	92	+3.0	+2.9	94	94	7.8	7.8
July 18	22.6	21.1	8.3	7.0	95	78	+1.6	+2.5	93	94	8.0	7.9
August 5	--	--	8.1	4.9	--	--	-1.1	+2.4	92	98	8.2	7.7
August 23	20.95	20.95	8.6	8.4	96	93	-1.6	-1.3	92	92	8.1	8.1
September 6	--	--	8.4	8.2	--	--	-0.4	-0.8	92	92	8.0	8.1
September 19	20.7	20.7	8.6	8.6	95	95	-2.2	-2.5	94	94	8.3	8.3
October 2	17.4	16.9	9.3	9.1	96	93	--	--	103	98	8.2	8.2

supersaturated; but on May 21, when the plankton was at its height, the water was only 89 per cent saturated. There was no evidence of marked withdrawal of oxygen following the decline of the plankton, as there was in 1929. Apparently other factors, such as temperature and sunlight, tended to mask the relationship on the dates that samples were taken. On several dates there were marked differences between top and bottom samples as a result of temporary stagnation of the lower water. The smallest amount at the bottom was 4.9 parts per million on August 5. Presumably this represented a very low per cent of saturation, but temperatures are not available to determine this point. On August 9 the temperature at the bottom was 18.2°, which was almost 3 degrees lower than on July 18. If we assume that the bottom temperature on August 5 was also 18.2°, the water would have been only 52 per cent saturated.

The pH at the surface ranged from 7.8 to 8.3. In general, changes in pH were in agreement with changes in free carbon dioxide. At the bottom, pH ranged from 7.6 to 8.3. The lowest value accompanied the largest amount of free carbon dioxide. The most marked difference between surface and bottom (0.5 unit) was observed on August 5. On September 6 the pH was higher at the bottom than at the surface.

Methyl orange alkalinity ranged from 89 to 103 parts per million. With few exceptions the amounts at the surface and bottom were nearly the same. In general the spring samples showed a smaller amount than the summer samples and there was a decrease in early fall, but the surface sample of October 2 was unusually high.

A comparison of the data for 1929 and 1930 brings out some notable differences. Air temperatures during the period May-September, 1930 were considerably higher than for the corresponding period in 1929 (Table 4). Since the surface water warmed more rapidly, there was greater resistance to mixing and the lower water was kept from contact with the air for longer periods. As a result, the differences in chemical conditions between surface and bottom were more pronounced. Another difference between the two years was the greater length of time in 1930 during which there was an excess of free carbon dioxide. A deficiency of the gas at the surface was observed only once prior to August, whereas in 1929 there was an excess on only one occasion. A third difference was in the absence of a definite relationship between the chemical conditions and the abundance of plankton, particularly in the spring.

Station 158. Samples were taken here on 12 dates between early April and early October. The data are shown in Table 19. Conditions at this station and Station 37A were so similar that there is no necessity for a detailed account.

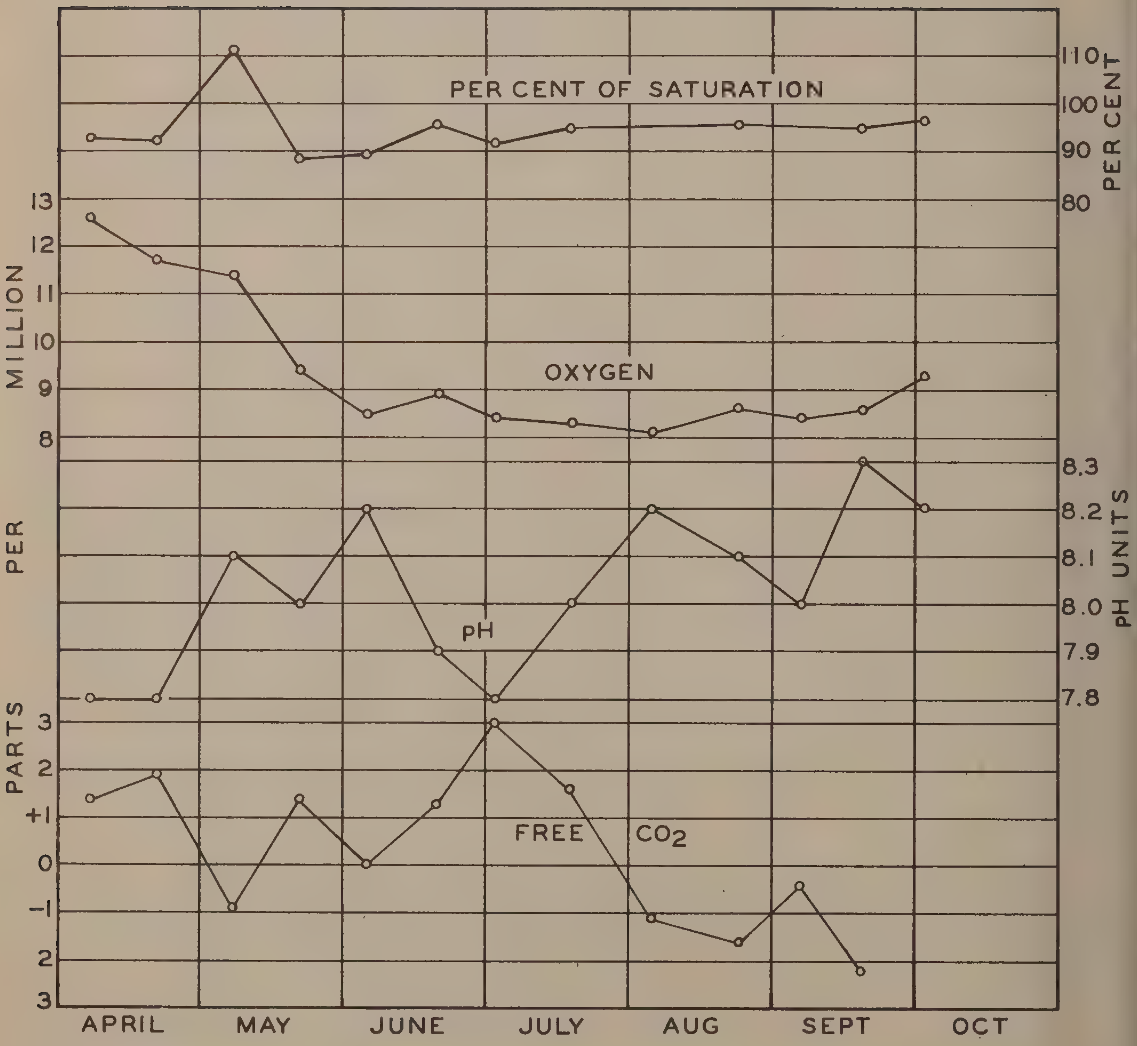

Fig. 12--Dissolved oxygen, free carbon dioxide, methyl orange alkalinity, and pH of the surface water at Station 37A, 1930. Compare with Figure 11. Data taken from Table 15.

The principal difference between the two stations was that at Station 158 the temperatures, and hence chemical conditions, were nearly uniform from top to bottom on the days when samples were taken. The stations differed also in that, at Station 158, there was a closer relation between the amount of oxygen and the abundance of phytoplankton. The surface water was farthest from saturation (83 per cent) on June 11, when the spring crop of plankton was declining, and was supersaturated in September, when the plankton was again abundant. However, on May 17, when the spring crop of plankton was at its height, the water was only 89 per cent saturated.

The seasonal changes in free carbon dioxide and pH were similar at the two stations. Methyl orange alkalinity was generally lower at Station 158. The highest values were recorded in the summer and lowest in the spring, with the fall values lower than those of summer but not as low as those of spring.

Station 8F. Sampling was not begun at this station until May 8. The data obtained here on 10 dates are shown in Table 20.

In most respects the conditions were similar to those found at Stations 158 and 37A. The differences between surface and bottom samples were more pronounced, in certain cases, than any found at Station 158, but there were no cases of marked depletion of oxygen such as the one observed at Station 37A on August 5, or at Station 59A on August 9. There was an excess of free carbon dioxide in all samples taken prior to September 5. An unusual feature of the record at this station was the fact that the surface water remained at pH 8.0 in spite of changes in free carbon dioxide over the range -0.4 to +1.7 parts per million. This lack of change in pH can be explained partially by changes in the carbonate content, but obviously some other unknown factor was

Table 19.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 158, 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
April 4	2.9	2.85	13.0	12.6	96	93	+1.9	+1.9	85	85	7.7	7.7
April 20	6.95	6.1	11.1	11.0	91	88	+1.9	+1.9	85	85	7.8	7.8
May 6	12.05	9.7	10.4	10.4	96	91	+0.7	+1.7	89	89	8.0	7.9
May 17	14.1	14.0	9.2	9.0	89	87	+1.4	+1.9	92	92	8.0	8.0
June 11	16.5	16.5	8.2	8.1	83	82	+1.4	+1.9	89	89	7.9	7.9
June 26	22.6	21.7	8.4	8.5	96	96	+1.8	+2.5	91	90	8.0	8.0
July 15	22.6	21.9	8.1	7.8	93	88	+3.1	+2.8	93	92	8.0	8.0
August 1	26.0	24.2	7.9	7.2	96	85	0.0	+0.5	92	90	8.1	8.0
August 19	22.7	22.35	8.1	7.7	93	88	-0.4	0.0	91	91	8.1	8.0
September 5	22.85	21.5	9.0	8.4	103	94	-1.5	-0.6	88	88	8.2	8.1
September 18	21.6	20.6	9.0	8.4	101	93	-2.3	-0.9	90	89	8.3	8.1
October 1	16.9	16.4	--	8.8	--	89	--	--	--	91	--	8.1

Table 20.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 8F, 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
May 8	11.6	7.8	11.1	10.6	102	89	+0.5	+1.4	87	88	8.0	7.9
May 23	14.7	12.8	9.1	8.9	89	84	+1.4	+2.2	86	90	8.0	8.0
June 12	17.0	16.0	8.2	7.7	84	77	+0.5	+1.2	89	89	8.0	8.0
June 25	21.5	18.7	8.7	6.8	98	72	+1.5	+5.0	95	95	8.0	7.8
July 12	22.2	21.8	8.0	7.8	91	88	+1.7	+2.2	92	92	8.0	8.0
August 1	24.1	23.7	7.4	7.1	87	83	+1.0	+1.0	90	90	8.0	8.0
August 19	21.95	21.9	8.0	7.9	90	89	+1.1	+0.5	86	86	8.0	8.0
September 5	22.2	21.3	8.3	8.4	94	94	-0.4	-0.9	87	86	8.0	8.1
September 24	19.8	19.7	8.6	8.4	93	91	0.0	0.0	87	85	8.0	8.0
October 3	16.7	16.65	--	8.8	--	90	--	+0.5	--	90	--	8.0

involved. Methyl orange alkalinity showed a distinct seasonal change; it was low in spring and fall, and high in summer. It may be seen that on three dates (August 1 and 19, and September 5) samples were taken both at Station 8F and Station 158. In each case a higher surface temperature was observed at Station 158, and there was a greater difference in temperature between top and botton at 158 than at 8F. In each case, also, there was more oxygen, less free carbon dioxide, and higher pH, at the surface of Station 158 than at Station 8F. These differences are believed to be due, in part at least, to the fact that Station 8F was visited in the morning and Station 158 in the afternoon. Longer exposure to the sun at Station 158 would account for the higher surface temperature, greater temperature gradient, and greater activity of photosynthetic organisms. In each case the bottom waters at the two stations were much the same in temperature, and in chemical constituents, as far as the latter were observed.

General discussion

The data on dissolved oxygen, carbon dioxide, and pH presented in the preceding pages are believed to be representative of the Island Section for the period of time covered, that is, from early April to late October. Additional data from other stations for the same period are at hand, but they show essentially the same features as those already given.

According to the figures presented in Tables 14-20, and in the accompanying text, the oxygen content of the surface water ranged from 7.1 to 13.0 parts per million. The per cent of saturation with oxygen ranged from 83 to 133, but almost all of the samples showed a saturation between 90 and 99 per cent. With a few exceptions the lower oxygen values, that is, those below 90 percent of saturation, were correlated with a decline of plankton. There is no reason to believe that low oxygen content of the surface water was ever the result of pollution.

Oxygen content of the bottom water ranged from 0.78 to 12.6 parts per million, and from 8.6 to 105 per cent of saturation. The very low value indicated was found at Station 59A on August 9, 1930, near the end of a period of thermal stratification. It is not known exactly when the stratification was established, but it certainly was after July 24, so that the lower water had been isolated from the air not more than 16 days. This may appear to be a very short time in which to bring about nearly complete exhaustion of oxygen. However, in Lake Mendota in 1906, almost all of the oxygen at the bottom was removed two weeks after stratification, even though the temperature was less than 12° (Birge and Juday, 1911, Plates I and II). At Station 59A the temperature at the bottom was 20.7°, and decomposition would proceed much more rapidly at that temperature than at 12°. Thus the low oxygen at Station 59A (and at Station 37A at about the same time) can be explained on natural grounds, and it is not necessary to assume the presence of polluting materials. The case cited is the only one of marked depletion of oxygen observed in the three seasons of investigation. One sample in 1928 showed only 62 percent of saturation, and in 1930 a few samples showed less than 80 per cent, but in most cases the bottom water was nearly as well supplied with oxygen as the surface water.

Since free carbon dioxide and pH vary closely with the oxygen, it will not be necessary to discuss them in detail. Free carbon dioxide in the surface water ranged from -5.9 to +3.1, and in the bottom water from -3.0 to +7.3. The last value (+7.3) was associated with the very low oxygen at Station 59A, and was unusually high. Values in excess of +3.0 were rare. The pH of the surface water ranged from 7.7 to 8.5, and of the bottom water from 7.3 to 8.3.

The data give every indication of being normal, that is, they are essentially the same as those from some shallow inland lakes which are not polluted. Lake Wingra, Wisconsin is a lake of this type which has been studied in detail (Tressler and Domogalla, 1931). In May of both years reported, the water was supersaturated with oxygen, but during the remaining months of the period April-October it was always less than saturated, with a minimum of 75 per cent. Lake Wingra showed a consistent deficiency of free carbon dioxide during the period in question, and in some cases reached -10 parts per million. Western Lake Erie never became so deficient in carbon dioxide, and commonly contained a small excess, particularly in 1930. The pH of Lake Wingra was somewhat higher than that of Lake Erie in general, but the maximum (pH 8.7) was only slightly higher. On the whole the two lakes agree very closely with repsect to oxygen, free carbon dioxide, and pH - as closely as one would expect in bodies of water so far apart.

It is commonly believed that the surface water of an unpolluted lake must be saturated or very nearly saturated with oxygen. This idea is untenable. Juday and Birge (1932) reported that half of a large number of surface samples from lakes in northeastern Wisconsin fell between 83 and 93 per cent of saturation, and more samples fell in the 86-87 per cent group than in any other group of like interval. Many surface samples from lakes free from a noticeable amount of humic substances were well below the saturation point, even when the influence of elevation of the lakes on the saturation point is taken into consideration. It is not uncommon to find marked reductions in oxygen content of surface waters as a result of the death and decomposition of plankton organisms (see Whipple, 1927, page 209-210). The point to be made in this connection is that the fairly consistent lack of complete saturation in the Island Section was not necessarily the result of pollution.

Thus far no mention has been made of methyl orange alkalinity. In the Island Section this ranged from 85 to 103 parts per million of calcium carbonate. According to the classification of Birge and Juday (1911, page 76), Lake Erie may be regarded as a lake with medium hard water, approaching the lower limit of the hard water lakes. In general the methyl orange alkalinity was higher in summer than in spring or autumn, but there were some notable exceptions to that rule. As would be expected, the vertical distribution was uniform or nearly so in most cases, and when there were differences they seemed to be fortuitous.

Chloride and Nitrogen

Determinations of chloride and nitrogen were made only in the months of July, August and September of 1930. In the Island Section samples were taken at Stations 18, 37A, 59A, 158, 72, and 8F (Fig. 1). Samples were taken at the surface and near the bottom. In general the two samples agreed very closely; so closely that it is unnecessary to present both sets of data. In Table 21, only the means are recorded and in Table 22 the data are further summarized by recording the mean of the means for each station, and for all stations combined.

Reference to Table 21 shows that the earliest sample was taken on July 11, and the latest on September 24. This period of time is too short to give much information on seasonal changes, especially because the sampling program was somewhat irregular and did not include all stations in each period of two weeks. Only in the nitrate nitrogen was there a change sufficiently definite and consistent to be regarded as an undoubted seasonal change. During the period covered by the chemical determinations, the phytoplankton increased, slowly at first and rapidly later (Fig. 14). Along with this increase there was a fairly general decline in the amount of nitrate nitrogen. At every station except 8F, the last determination of the season was the lowest, and at Stations 18 and 72 the downward trend was unbroken. The decline in nitrate was due, very probably, to rapid withdrawal by the multiplying plants of the plankton.

Among the other forms of nitrogen, the changes were so irregular and inconsistent that no definite connection with the changes in abundance of phytoplankton is evident. Probably a more regular sampling program carried on over a period of several months would show definite seasonal trends such as were found by Domogalla et al. (1925 and 1926). However, perfect correlation between nitrogen and the plankton is not to be expected because of the complexity of chemical and biological processes in a lake. Changes in the nitrogen compounds are continually taking place as a result of the activities of ammoniafying and nitrifying bacteria, and of the chlorophyllaceous plankters. In view of the inadequacy of the data at hand, further discussion of the question will be omitted from this report.

The amount of chlorine as chloride ranged from 8.6 to 11.7 parts per million with a mean for all stations of 10.3 (Tables 21 and 22). Station 8F was the only one to show chloride below 10.0 consistently. It will be shown later that Detroit River is quite consistently low in chloride, and it seems probable that the northern location of Station 8F makes it subject to the influence of water from the river more than are the other stations. The extreme range noted above (8.6-11.7) was recorded for Station 72, the most westerly of the stations. Except for the single low value, chloride was consistently above 11.0, and the mean for all dates was 10.9. Probably this station is usually affected by water from the southwest corner of the lake, where chloride is regularly high, and only occasionally by water from the more distant Detroit River. Stations other than 72 had rather small variations in the amount of chloride.

Table 21.- Chloride and nitrogen in parts per million at stations in the Island Section, 1930

Station	Date	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3
	July 21	10.3	0.015	0.260	0.008	—
	August 6	10.3	.018	.143	.007	0.15

Table 22.- Mean chloride and nitrogen in parts per million at stations in the Island Section for the period July - September, 1930. Data derived from Table 21.

Station	No. of dates sampled	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3
18	4	10.2	0.013	0.163	0.008	0.10
37A	5	10.5	.009	.149	.007	.11
59A	5	10.5	.014	.182	.002	.06
158	5	10.5	.012	.153	.005	.12
72	5	10.9	.014	.146	.004	.09
8F	5	9.4	.015	.115	.006	.11
Mean	---	10.3	.013	.151	.005	.10

Free ammonia (that is, nitrogen as free ammonia) ranged from a low of 0.002 to a high of 0.033 part per million in the various samples. However, the means for the stations agreed quite closely; they ranged from 0.009 to 0.015, with a mean of 0.013 for the whole area. Albuminoid ammonia ranged from 0.100 to 0.260 in the samples, and from 0.115 to 0.182 in the station means, with a mean of 0.151 for the area. Thus, on the average, the amount of albuminoid ammonia was about 12 times as great as the free ammonia.

The most rare form of nitrogen was nitrite, which ranged from 0.000 to 0.014 in the samples, and from 0.002 to 0.008 in the station means, with a mean of 0.005 for the area. Nitrate was consistently more abundant than nitrite, ranging from 0.02 to 0.24 in the samples, and from 0.06 to 0.12 in the station means, with a mean of 0.10 for the area. On the average, then, nitrate was 20 times as concentrated as nitrite.

Table 23 permits a comparison of the Island Section of Western Lake Erie with several other waters with respect to the concentration of chloride and compounds of nitrogen. It is not known when Mason (1917) took his samples. Otherwise, with the exception of the data from Whipple (1913), which were taken in August only, the data in this table are based on samples taken in the months of July, August, and September. The figures on Lake Erie at Cleveland and on Lake Michigan at Lake Forest are based on samples taken in two successive years. In each case the figures represent means of several samples.

The amount of chloride in the Island Section was decidedly higher than in the pure waters reported by Mason, and higher even than in the polluted waters. Concentration of chloride is regarded as a valuable index of the degree of contamination by domestic sewage and certain types of trade wastes, provided the normal chloride content of the water is known. A lake may have a high chloride content and yet not be polluted, for tributary streams may bring in water which has come in contact with deposits of salt. Thus the high chloride of the Island Section as compared with the pure and polluted waters reported by Mason is not, in itself, evidence of pollution. The significance of the high chloride content of Lake Erie will be taken up in later pages of this report, following the presentation of data on the streams entering the lake at the west end. It will suffice to say here that the chloride is derived from both natural and pollutional sources of sodium chloride. That the amount of chloride present (10.3 parts per million) is far too small to be harmful to organisms scarcely need be stated.

The results of analyses for nitrogen given in Tables 21 and 22 probably would lead a sanitary engineer to regard the water as unsuitable for domestic consumption before treatment. The frequent presence of albuminoid ammonia in excess of 0.15 part per million, and the presence of considerable amounts of nitrite would suggest pollution at once. The samples showing albuminoid ammonia in excess of 0.20 part per million would be open to suspicion particularly. It is entirely possible that such values are normal to the lake, but in view of the fact that the lake is subject to pollution by domestic sewage from many sources, it is difficult to escape the conclusion that the nitrogen

Table 23 .- Comparison of the amounts of chloride and nitrogen in parts per million in several waters

Source of water	Year	Authority	Cl as chloride	Nitrogen as			
				Free NH_3	Albuminoid NH_3	NO_2	NO_3
Lake Erie, Island Section	1930	This report	10.3	0.013	0.151	0.005	0.10
Sundry pure surface waters	---	Mason, 1917	3.6	.063	.066	.000	.14
Sundry polluted surface waters	---	Mason, 1917	6.1	.182	.228	.006	.75
Lake Erie, Cleveland water supply	1910 and 1911	Jackson, 1912	10.0	.030	.076	.002	.30
Lake Erie, eastern end	1928	Burkholder, 1929	---	.016	.087	---	.14
Lake Ontario, off Rochester	1912	Whipple, 1913	8.2	.043	.113	.001	.12
Lake Michigan, Lake Forest water supply	1907 and 1908	Bartow, 1909	4.2	.062	.168	.001	.17

ontent has been increased by pollution. In that sense the Island Section hould be regarded as polluted, but the comparative figures in Table 23 show hat it is not heavily polluted.

The data in Table 23 show that the Island Section contained on the average lmost the same amount of nitrogen as the pure waters reported by Mason, lthough the proportions of the different forms of nitrogen were different in he two waters. Aside from any consideration of potability, there seems to be ittle choice between the two with regard to suitability for aquatic organisms. ertainly the resemblance is closer than between the Island Section and the olluted waters reported by Mason. On the basis of these comparisons, the ater of the Island Section may be regarded as relatively pure. Comparisons ith other parts of the Great Lakes as given in Table 23 do not point to heavy ollution in the Island Section.

The data in Table 22 show some points of interest on the question of ollution. Of the six stations, Station 59A had the largest amount of albuminoid ammonia. This station is located near Sandusky Bay and probably is affected by polluted water from that source at times. Station 8F had the smallest amount of albuminoid ammonia. Station 8F has the most northerly location of those in the Island Section, and probably is affected by water from Detroit River more than the other stations. This is suggested by the fact that Detroit River is quite consistently low in albuminoid ammonia and in chloride (Table 46). There is no evident relationship between the amount of nitrogen at the remaining stations and their location with respect to sources of pollution.

Conclusions Regarding Pollution

Pollution by domestic sewage may change a number of the normal characteristics of a lake. Perhaps the most obvious chemical change is the reduction f the oxygen content, which results from the mineralization of nitrogen compounds contained in the sewage. With sufficiently heavy pollution, all of the dissolved oxygen may be withdrawn from the water. Pronounced reduction f the oxygen supply is undesirable because most of the organisms normally present in a lake require a large supply, and they disappear when it is not available. For that reason pollution may be regarded as harmful to a lake. However, the water may be so lightly polluted that the oxygen withdrawals cannot be distinguished from those of natural origin. Under such conditions it is safe to conclude that the pollution has no harmful effect on the water, provided, of course, that poisonous chemicals are not present.

This seems to be the case in the Island Section. In discussing the data on oxygen, it was pointed out there was no evidence of oxygen reductions due to pollution. The data on nitrogen tend to confirm this conclusion. While it is probable that the nitrogen content has been increased by pollution, it is equally probable that the additional demand upon the dissolved oxygen has been small as compared to demands resulting from natural phenomena, such as the decomposition of plankton organisms. Thus, from the chemical point of view, the water of the Island Section seems to have been affected very little by polluting materials known to enter the lake.

Sewage Dilution in the Tributaries

This investigation did not include a survey of the sources of pollution on the shores of the streams entering the lake, but it is known that they are numerous and of divers types. In the following pages, the chemistry of the lake water near the mouths of four of the streams will be considered. Interpretation of the results will be aided somewhat by a brief consideration of the size of the streams and the concentration of population on their banks, particularly near their mouths.

Portage River is the smallest of the four streams. The discharge at the mouth is not known, but certainly during the low water period in summer it is small, for water frequently flows into the river from the lake. According to observations made in the north branch of the river near Bowling Green, Ohio, the discharge is subject to wide fluctuations, with the highest water usually in winter and spring, and the lowest in summer and autumn (U.S. Geological Survey, 1927-1932). There are no large centers of population on the river. The principal source of sewage in the lower river is Port Clinton (population 4,408), which is situated at the mouth. Ninety per cent of the city's sewage enters the river, and the remainder enters the lake nearby. In spite of the lack of definite knowledge of the volume of discharge of the river, intense pollution near the mouth is not to be expected, even at times of minimum discharge, because of the added dilution which results from the frequent inflow of lake water. However, current reversals in the river depend upon highly variable physical factors, and it would be impossible to predict the frequency of their recurrence, or their degree of influence on dilution in the river. There is every reason to believe that, following discharge, dilution should prevent any marked effect on the water of the lake.

The discharge of Maumee River at the mouth is not known, but at Waterville, Ohio, about 25 miles above the mouth, the combined discharge of the river and canal for a period of nine years (1922-1930) was 5,417 cubic feet per second (U.S. Geological Survey, 1925-1932). Presumably the discharge at the mouth is only slightly more than at Waterville, for no large tributaries enter below that point. The flow is subject to large seasonal fluctuations. For example, in 1930 it ranged from 63 second-feet on July 15 to 72,600 second-feet on January 16. The mean discharge in July, August, and September for a nine year period was 1,584 second-feet; it was somewhat higher in the same months of 1929 (2,159 second-feet); but in 1930 it was exceptionally low (201 second-feet). Obviously the volume of water available for dilution of sewage varies widely within the same year, and also for the same period in different years. The river drains a populous district and receives a large amount of sewage. As early as 1898 there was definite chemical and bacterial evidence of pollution at several points in the river, and the subsequent growth in population doubtless has caused an increase in intensity of pollution. The principal source of sewage in the lower part of the river is Toledo, Ohio, situated at the mouth. The population of Toledo in 1930 was 290,718, so that with mean discharge (5,417 second-feet) there would be 54 individuals for each second-foot of river water available for dilution. In periods of low water this figure would be increased considerably; during July-September, 1929, it was 135 per second-foot, and in 1930 the corresponding figure was 1446. The International Joint Commission (1918) concluded that a stream with a discharge of less than 4 second-feet for each contributing person was unsafe as a source of drinking water unless treated. The wide discrepancy between this figure and those given for Maumee River at Toledo during periods of small discharge leads one to expect heavy pollution at the mouth, particularly when it is recalled that the water is polluted before reaching Toledo. Inflow of lake water increases dilution in the lower part of the river periodically, so that marked variations in the intensity of pollution in a single day are to be expected.

The flow of River Raisin has not been measured accurately. From estimates of the run-off per square mile made by McNamee (1930, page 56), the mean annual discharge has been calculated to be about 675 second-feet. According to estimates given in an unpublished report by Professor Jacob E. Reighard, the mean discharge for July, August, and September of 1918, 1919, and 1920, was 197 second-feet. Nothing is known of the discharge during the same period of 1928, 1929, and 1930, when most of the chemical samples were taken in this section. In all probability it was very low in 1930 here, as in Maumee River. There are no large cities contributing sewage to River Raisin, and according to McNamee, (1930) the total sewered population is only 37,787. Yet the volume of sewage is large for a stream of such small discharge. Monroe, Michigan, with a population of 18,110, is the main source of sewage near the mouth of the river. At times of mean discharge there would be, near the mouth, 27 contributing persons per second-foot; and for the months of July, August, and September (using the mean for 1918, 1919, and 1920) there would be 92 persons per second-foot. However, these figures do not give an adequate idea of the intensity of the pollution, because as McNamee pointed out, the watershed is characterized by a comparatively high proportion of waste-producing industries for its size. For example, paper mills at Monroe during normal activity discharge volumes of waste which may well approach or exceed the domestic sewage of Monroe in polluting capacity. Periodic inflow of water from the lake should increase dilution in the lower river, but in view of the large amount of wastes entering in that region, definite chemical evidence of pollution is to be expected at times of small discharge.

Detroit River is the principal tributary of Lake Erie. With average height of water in Lake Huron and Lake Erie, its discharge is approximately 204,000 second-feet. Discharge of the river is not subject to such large fluctuations as the smaller streams. However, according to figures obtained from the United States Lake Survey, retardations of 40-50 per cent due to ice blockades are not infrequent in March and April. When the river is free from ice, reductions in excess of 25 per cent of the mean are to be expected very rarely. During the periods when chemical samples were taken in the present investigation, the discharge was not far from the mean. The population of municipalities contributing sewage directly to the river in 1930 was 1,850,340. Therefore, with mean discharge, there would be 9 contributing persons per second-foot. This figure is well above that which was regarded as allowable by the International Joint Commission, but is much lower than that of Maumee River and River Raisin during the months of July, August, and September. For these months less intense pollution is to be expected in Detroit River at the mouth than in the two rivers just mentioned.

In fact there is reason to believe that Detroit River at the mouth would show little or no chemical evidence of pollution at times of normal flow. Frost, et al. (1924, pages 174-178) were unable to detect, with certainty, the effect of sewage from Cincinnati on the nitrogen content of Ohio River when the discharge exceeded 50,000 second-feet. At the time the analyses were made the contributing population of Cincinnati was roughly 500,000 so that the degree of dilution with a discharge of 50,000 second-feet would be about the same as in Detroit River, with a contributing population of nearly two million and a discharge of 200,000 second-feet. It is questionable whether Detroit River would show very definite chemical evidence of pollution at the mouth even at times of minimum flow. Conditions affecting dilution in Detroit River will be given further consideration in connection with the discussion of results.

All except a few of the chemical samples were taken when the lake was free of ice, and when the streams other than Detroit River were discharging less than the mean annual amount of water. It seems probable that, at times of maximum discharge, dilution in these streams would be so great that it would be difficult or impossible to detect sewage pollution by the usual chemical analyses. For example, on January 16, 1930, the dischrage of Maumee River was 72,600 second-feet, so that there would be only four contributing persons per second-foot of discharge at Toledo, or less than one half the number for Detroit River at times of mean flow.

Portage River Section

Oxygen, carbon dioxide, and hydrogen-ion concentration

Chemical samples were taken in this area only in 1929 and 1930. The only point at which samples were taken regularly was Station 159, located 1/4 mile north of Port Clinton Light, which is at the mouth of the river. The depth at this station is 3.5 meters. The data obtained on 15 dates in the two seasons are shown in Table 24. Because of the meager depth and action of waves, the temperature was usually almost the same at top and bottom; the greatest observed difference was 0.9°. On several occasions, both surface and bottom samples were taken, but the differences were too small to have any importance.

Table 24.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 159 in 1929 and 1930. Samples in 1929 from the surface; in 1930 from 3 meters. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
			parts per million	per cent saturation			
1929	May 21	13.35	8.8	84	+3.5	145	7.8
	June 18	22.35	7.9	90	0.0	102	8.0
	July 6	22.65	7.8	89	0.0	109	8.1
	July 26	23.45	8.2	95	-3.3	100	8.2
	August 16	20.9	8.3	92	-3.0	98	8.3
	September 24	17.95	9.3	97	-1.3	98	8.1
	October 10	12.4	10.5	98	-0.4	95	8.1
1930	May 13	14.4	9.9	96	-0.4	100	8.1
	June 17	19.6	8.5	92	+2.8	94	7.8
	July 6	21.7	8.1	91	+1.4	97	8.0
	July 26	25.1	7.7	92	+0.5	94	8.1
	August 4	24.2	7.6	89	-1.7	101	8.5
	August 22	20.9	8.5	94	-1.8	94	8.3
	September 2	22.65	8.4	96	-2.4	95	8.3
	September 16	21.6	7.6	86	-1.4	98	--

There are no evidences, in the table, that the water at Station 159 was unfavorably influenced by water from the river. There was always an ample supply of dissolved oxygen. The water was usually more than 90 per cent saturated and never less than 84 percent. On only four occasions was there an excess of free carbon dioxide, and frequently the deficiency was rather marked. The lowest pH reading was 7.8. Methyl orange alkalinity was consistently high and on one date (May 21, 1929) it was much higher than any value obtained in the Island Section. In other respects the data are the same kind as those found at Stations 37A, 158, and 8F.

The discharge of Portage River is small, and the current reverses periodically. Even when the current is out of the river, the discharged water is commonly deflected by littoral currents, and does not reach Station 159. In order to learn something about conditions in the river itself, a number of samples were taken at Station 160, near shore at the foot of Madison Street in Port Clinton (depth, 3 meters). If the river were badly polluted, one would expect to find chemical evidence of it at this point.

The data as given in Table 25, afford little or no evidence of pollution. On August 4, when there was no noticeable current in the river, the water was only 77 per cent saturated with oxygen, but similar results were occasionally recorded for stations in the open lake, far from sources of pollution. On August 22, when the current was directed up-river, the water was nearly saturated, and on September 16, when the current was outward, the water was only 83 percent saturated. This difference may have resulted from a difference in the photosynthetic activity of the algae, for the sky was clear on August 22, while it was overcast on September 16. The data for free carbon dioxide and pH agree with those for oxygen in failing to show definite evidence of pollution. The data reported by Osburn (1926a) are much the same as those reported here. A sample taken at the mouth of the river on August 9, when the current was outgoing, showed 6.7 parts per million of oxygen (79 per cent of saturation), and pH 8.4. Stations in the lake near the river had a somewhat higher content of oxygen. At one station the water was 94 per cent saturated, and the pH was 8.6.

It should not be concluded that the river is free from pollution, but only that, on the days when samples were taken, the amount of polluting matter was not sufficiently great to cause a marked withdrawal of oxygen, with the associated changes in carbon dioxide and pH. It is conceivable that under unusual conditions there would be pronounced oxygen depletion in the river. But it is doubtful whether such unusual conditions would ever persist long enough to make the river an important contributor of oxygen-free water to the lake.

Chloride and nitrogen

Samples were taken at two stations in this section; at Station 159, a short distance out from the mouth of the river, and at Station 60, in the river near its mouth. The data are shown in Table 26.

At both stations there were marked differences in chloride and nitrogen on different dates, as would be expected from the fact that the current of the river reverses periodically. Because of the constantly changing conditions here, it would be necessary to take many more samples to determine averages accurately. But in spite of the small number of samples taken, the results have some rather characteristic features which should be noted.

Table 25.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 160 (Portage River at Port Clinton), 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
		parts per million	per cent saturation			
July 26	26.05	6.8	83	+1.0	99	8.0
August 4	24.0	6.6	77	-1.1	109	8.1
August 22	22.55	8.7	99	-1.8	96	8.3
September 2	23.1	8.4	97	-2.2	97	8.2
September 16	21.6	7.4	83	-1.5	99	8.1

Table 26.- Chloride and nitrogen in parts per million at Stations 159 and 160 (Portage River Section), 1930

Station	Date	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3
159	July 6	12.2	0.008	0.251	0.002	0.03
	July 26	11.8	.032	.242	.002	.14
	August 4	17.4	.006	.260	.000	.08
	August 22	11.6	.000	.187	.001	.04
	September 2	12.9	.000	.198	.001	.02
	September 16	22.7	.012	.216	.002	.04
160	July 26	18.3	---	---	.001	.04
	August 4	40.0	.036	.368	.001	.08
	August 22	11.7	.034	.196	.001	.02
	September 2	18.2	.012	.272	.001	.00
	September 16	18.4	.012	.276	.001	.04
159	Mean, six dates	14.8	.010	.226	.001	.06
159	Mean, four dates	16.2	.004	.215	.001	.05
160	Mean, four dates	22.1	.024	.278	.001	.04

Comparison of the two stations on the four dates for which comparable data are available shows that the station in the river had, on the average, more chloride and free and albuminoid ammonia than the station in the lake. This finding is entirely consistent with expectation because the river is contaminated by sewage. Nitrite was the same at both stations, and nitrate was nearly the same, although we should expect the river station to have more of both forms of nitrogen. The mean values of nitrogen for these stations are not strongly indicative of pollution. Compared with the mean for stations in the Island Section (Table 23), only albuminoid ammonia was notably high, while nitrite and nitrate were decidedly lower. Compared with the polluted waters reported by Mason, all forms of nitrogen except albuminoid ammonia were low. It may be concluded that the water of the river and of the lake nearby is not heavily contaminated by sewage. Yet the rather high results for albuminoid ammonia point toward pollution in some degree. The question arises, why are the other forms of nitrogen so low - in the case of nitrite and nitrate much lower than in the Island Section? Consideration of this question will be deferred until similar results for the Maumee Bay Section have been presented.

The Ohio State Board of Health (1902) made a study of the water at the Port Clinton intake, which was some distance west of Station 159. One sample was taken in each of the months of April, June, July, and August, 1901. The results obtained showed great variation. Chloride ranged from 12.9 to 147.7 parts per million; nitrite from a trace to 0.030; and nitrate from a trace to 1.58. Free and albuminoid ammonia were less variable with means of 0.046 and 0.184 part per million, respectively. Because of the wide variations, and the difference in position of the stations, it probably would be unprofitable to attempt to draw conclusions from a comparison of these data with those obtained in 1930. The high chloride of the earlier samples was believed to result from the use of salt in the fishing industry at Port Clinton.

Conclusions Regarding Pollution

The data on oxygen and nitrogen obtained in 1930 lead to conclusions similar to those reached for the Island Section. Nitrogen determinations indicate light pollution of the water of the river and the lake near its mouth, but apparently the added demand upon dissolved oxygen has not been great. In view of the small discharge of the river and low intensity of pollution, Portage River may be regarded as of little importance in contributing polluted water to the lake.

Maumee Bay Section

Oxygen, carbon dioxide, and hydrogen-ion concentration

Season of 1928

In 1928, samples were taken at three stations in the vicinity of Maumee

Bay. It has been found expedient to present the data from two of these stations with data from the same stations in 1930. For the present only the data from Station 254 will be considered. This station is across the channel from Toledo Harbor Light, and 8-1/2 miles from the mouth of Maumee River. The depth is 6.2 meters. The data obtained here are given in Table 27.

On three of the four dates there were noticeable differences in the chemical constituents at the surface and bottom. There was an abundance of oxygen in all the samples; in four cases the water was supersaturated, and in no case less than 90 per cent saturated. Associated with this abundance of oxygen there was a deficiency of free carbon dioxide, and high pH. It hardly need be stated that the data afford no evidence of pollution. On the contrary, the data indicate that, at this point, the agencies responsible for oxygen production were more active than those responsible for oxygen consumption. This finding is corroborated by the data obtained in 1929 and 1930, which will be presented in the following pages.

Season of 1929

In 1929 it was decided that information concerning the chemical conditions nearer the source of pollution (Maumee River) should be obtained. Accordingly Stations 250 and 252 were established, at the mouth of the river and at the harbor range lights, respectively. The depth at Station 250 was 3 meters and at Station 252, 3.9 meters. Table 28 shows the data from these stations and Station 254. The data are arranged by dates so that changes in conditions can be traced from the mouth of the river out to Station 254. Only surface samples are shown. In no case was there a significant difference in temperature between the surface and bottom.

The current of Maumee River is subject to periodic reversals and, except at times of high water, is very weak. Since the water of the lower river is polluted, we should expect to find some correlation between the direction of the current and the chemical contents of the water at Station 250. That is, we should expect to find less oxygen and more free carbon dioxide at a time of outflow than at a time of inflow. Yet this would not necessarily be true, because if the water had just started to flow out following a long period of inflow, the water at Station 250 would be less contaminated than if it had just started to flow in following a long period of outflow. In all cases our knowledge of the current was restricted to the time that samples were taken.

On June 26, when the current was out of the river, there were only 1.4 parts per million of dissolved oxygen present, representing 17 per cent of saturation. A marked improvement was noted at Station 252 (4.5 miles distant) where the oxygen content had increased to 6.2 parts per million or 72 per cent of saturation. At Station 254 there was further improvement, but oxygen was low compared to the samples taken here in 1928, possibly as a

Table 27.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity (CaCO3), and pH at Station 254, 1928. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
			parts per million		per cent saturation							
	S	B	S	B	S	B	S	B	S	B	S	B
May 22	19	16.5	11.9	10.1	127	103	-5.9	-5.0	89	97	8.7	8.5
June 14	19.5	18	9.8	8.6	106	90	-4.4	-2.6	105	105	8.5	8.2
June 28	19.5	19.5	8.8	8.8	95	95	-2.0	-2.0	103	95	8.3	8.3
August 20	24.5	24	8.7	7.9	103	93	-5.9	-5.0	92	92	8.5	8.4

Table 28.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Stations 250, 252, and 254 in the Maumee Bay Section, 1929. All samples taken at the surface. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Station	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
			parts per million	per cent saturation			
June 26	[1]250	24.6	1.4	17	+12.5.	152	7.7
	252	23.9	6.2	72	+1.0	111	7.9
	254	21.25	7.2	80	0.0	95	8.0
July 17	[1]250	24.8	1.0	12	+10.7	118	7.5
	252	23.3	7.3	84	+0.5	118	7.9
	254	22.95	7.7	89	-1.5	93	7.9
August 3	[2]250	24.2	3.4	40	—	—	7.7
	252	23.2	8.3	96	—	—	8.4
August 23	[1]250	22.5	2.6	30	+10.3	154	7.6
	252	21.3	8.6	96	-6.0	109	8.4
	254	21.25	8.7	97	-6.5	98	8.6
September 7	[3]250	21.6	4.7	53	+3.2	127	7.8
	252	22.0	8.5	96	-3.5	109	8.3
	254	21.7	8.5	96	-3.5	91	8.4
October 4	[2]250	14.3	5.1	50	+4.8	125	7.7
	252	14.25	10.1	98	0.0	102	8.0
	254	14.1	10.0	97	-0.4	100	8.0

[1] Current out of river [2] No current [3] Current into river

esult of the lack of sunshine on the morning of June 26. The changes in xygen content were reflected in changes in free carbion dioxide and pH. ree carbon dioxide was high[4] at Station 250, but the excess was small at tation 252, and was entirely removed at Station 254. The pH ranged from .7 at the river to 8.0 at Station 254. Methyl orange alkalinity was 152 arts per million at the river, 111 parts per million at the range lights, nd only 95 parts per million at the harbor lighthouse. This change in ethyl orange alkalinity indicates that there is considerable mixing of he water from the river with that from the lake, even within Maumee Bay.

On July 17, the current was again out of the river and conditions at the hree stations were essentially the same as on the earlier date. The data or August 3 are incomplete, since Station 254 is not represented and certain of he analyses are lacking for the other stations. There was no current in the iver at the time samples were taken at Station 250. Judging by the relativey high content of oxygen (40 per cent), the current had been flowing into the iver and was about to undergo a reversal. If the current had been outward ust previously, it is probable that the oxygen would have been somewhat ower. At Station 252, oxygen content and pH were high.

On August 23 the flow was outward, but in this case oxygen depletion at tation 250 was less marked than on June 26 and July 17. At the outer staions oxygen was very high and the carbon dioxide deficit and pH were also igh. Conditions at the two stations were almost the same. As on June 26 here was a pronounced decrease in methyl orange alkalinity with increased istance from the river. On July 17 there was little change between the two nner stations.

When the samples were taken on September 7, the water was flowing from he bay into the river, and oxygen was nearer the saturation point than at ny time for which data are available in 1929. Free carbon dioxide was elatively low (but see footnote 4) and the pH high. At Stations 252 and 254, onditions were, as on the preceding date, the kind one would expect to find n the open lake, far from sources of pollution. On October 4 there was no oticeable current at Station 250. It is probable that it had been into the iver a short time before for the water was at almost the same point of oxygen aturation as on September 7. The changes with increased distance from the iver were much like those observed on earlier dates.

Season of 1930

The data of 1929 showed that there was a decided improvement in condi-

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/ Owing to the brown color of the water at Station 250, considerable difficulty was encountered in detecting the end-point in titration. The values recorded for this station on June 26, July 17, and August 23 are probably too high. On later dates the difficulty was overcome largely, if not entirely.

tions with regard to oxygen, carbon dioxide, and pH at a distance of 4.5 miles from the river. It seemed desirable to have data from a point nearer the river, hence Station 251 was established mid-way between Stations 250 and 252, or 2.25 miles from the river. Samples were taken also at Station 249, located at the foot of Madison Street in Toledo, 4.75 miles up the river from Station 250. The data from all of the stations are given in Table 29. At Station 249, samples were taken at 4 meters, and at Station 250 and 251 they were taken at 2 meters. At Stations 252 and 254 samples were sometimes taken at both surface and bottom, but no important differences were found. All data shown for these stations are from bottom samples except those for Station 254 on September 20, which are from the surface.

The data from Station 249 give definite evidence of pollution. In none of the samples was the water as much as 50 per cent saturated with oxygen, and in one was as low as 34 per cent. Accompanying the low oxygen there was a considerable excess of free carbon dioxide, reaching as high as +7.5 parts per million. The pH was low in every sample. Methyl orange alkalinity was consistently high; the values recorded for this station were the highest found during the present investigation. The Ohio State Board of Health (1899) made a study of Maumee River in 1898. At a point near Station 249 the per cent of saturation with oxygen ranged from 46 to 82, with a mean of 60 (five samples). At a point two miles from the mouth of the river, the mean percentage was 70. These figures would seem to indicate less intense pollution in 1898 than in 1930, which is entirely in keeping with expectation.

The data on oxygen at Station 250 show that there were no cases of extreme depletion such as were found in 1929. Samples were taken on two occasions when the current was flowing out of the river (August 28 and September 9), but on both dates the oxygen was unexpectedly high. In fact the 90 per cent saturation on August 28 would be considered unusually high, even if the water were flowing into the river. With two minor exceptions, the samples of 1930 showed a considerably higher per cent of saturation than those of 1929 at corresponding phases of the current. On September 20 the water was actually supersaturated.

Three possible explanations for the higher results of 1930 suggest themselves. First may be mentioned the possible influence of the set of the current prior to the time of taking samples. For example, the high results of August 28 would be less surprising if it were known that the current had been flowing into the river for some time, and had just started to flow out when the samples were taken. No data are available to test the validity of this explanation.

At the mouth of Genesee River, Whipple (1913) found that the warm river water floated on top of the cold water of Lake Ontario. It might be thought that the same phenomena occurs at the mouth of Maumee River, and that the higher oxygen of 1930 could be explained by the fact that samples were taken at a depth of 2 meters rather than at the surface, as in 1929. However, it was found that the upper 2 meters of water was essentially uniform in temperature on the several dates for which data are available. The differences of temperature between Stations 249 and 250 in Table 29 may be considered as resulting from mixing of water from the two sources. That considerable mixing occurs is shown by the fact that the methyl orange alkalinity at Station 249 was uniformly much higher than at Station 250.

The true explanation for the high oxygen of 1930 is probably to be found in the great abundance of plankton algae in that year. Reference to Table 56 will show that the counts were much higher in 1930 than in 1929 for corresponding times of the season. It is believed that the photosynthetic activities of such tremendous numbers of chlorophyll-bearing organisms would be ample to account for the unusually high oxygen values of 1930, as compared with those of 1929.

It will not be necessary to dwell at length on the results from the stations farther from the river. It will be noted that samples from Station 251 showed an improvement over those at Station 250 for each date for which data are available, and that on three of the four dates the improvement was marked. In some cases the oxygen content was higher at Station 251 than at Stations 252 and 254. Such differences may be accounted for by the greater abundace of algae at the inner station, assuming that the abundace at Station 251 was intermediate between that of Stations 250 and 252 (Tables 56 and 57). At Station 251, each sample showed a decided deficiency of free carbon dioxide, and high pH. At the two outer stations the pH never fell below 8.0. It is worthy of note that, with minor exceptions, there was a progressive decrease in methyl orange alkalinity from the river outward. The most pronounced change was found between samples from Station 249 and Station 250, indicating that considerable mixing occurs directly at the mouth of the river. In spite of the high oxygen values at all stations out from the mouth of the river, it is certain that much of the polluting material is still present in an uncompletely decomposed form. (Table 32). Apparently it becomes so diluted that the chlorophyll-bearing organisms are able to compensate for loss of oxygen in the process of decay. Agitation of the water by the wind also must help in replenishing the supply of oxygen and in liberating the excess carbon dioxide.

In view of the lack of evidence of pollution in Maumee Bay, except at the mouth of Maumee River, one would not expect to find such evidence along the shores outside of the bay. Table 30 shows the data obtained at two points near the south shore, east of Maumee Bay in 1928 and 1930. Stations 106 and 105 are one mile apart and lie in an area about two miles from the shore and four miles east of Little Cedar Point. Both surface and bottom samples were taken on several occasions but the results were so uniform that only bottom samples are recorded. Obviously the data offer no evidence of pollution.

Somewhat similar results were obtained at Station 116 in 1928 and 1930 (Table 31). This station is located 1-1/8 miles off the shore at Toledo Beach, Michigan, and 5 miles in a generally northwest direction from Toldeo

Table 30.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 106 (1928) and Station 105 (1930). Samples taken at approximately 4 meters. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
			parts per million	per cent saturation			
1928	June 12	16.5	9.3	94	-2.0	110	7.9
	June 28	19	8.7	93	-2.0	95	8.1
	August 20	24	7.9	93	-5.9	92	8.5
	October 30	13.5	9.5	91	-3.6	90	8.5
1930	July 3	21.25	8.6	96	0.0	95	8.2
	August 14	22.1	8.5	96	-2.6	90	8.3
	August 28	20.9	7.7	86	-0.5	96	8.1
	September 9	19.8	8.2	89	-1.7	92	8.2
	September 20	19.1	8.9	95	-3.2	95	8.4

Table 31.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 116 in 1928 and 1930: Samples taken at approximately 4 meters. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
			parts per million	per cent saturation			
1928	June 14	18	8.6	90	-2.4	120	8.2
	June 29	19.5	9.0	97	-2.0	99	8.1
	August 27	22	8.3	94	-7.9	97	8.7
1930	August 16	22.4	9.5	108	-4.7	93	8.8
	August 30	21.05	8.6	96	-3.4	97	8.5
	September 11	19.95	8.7	95	-4.5	94	8.7

arbor Light. Samples were taken on six dates in the two years. Only bot-
om samples are shown. As at Stations 105 and 106, there is an entire
bsence of evidence of pollution.

The results reported by Osburn (1926a) for the Maumee Bay region are in ssential agreement with those obtained in this investigation. On August 12, 926, samples were taken at four stations near Toledo Harbor Lighthouse and ittle Cedar Point. Oxygen was near saturation in all samples except one (a ottom sample), in which it was reduced to 78 per cent of saturation. The pH anged from 7.8 to 8.4. On August 18, the water at the mouth of Maumee River as 57 percent saturated, and had a pH of 7.8. The water of the bay on the ame day was as low as 72 per cent saturated which may have resulted from eather conditions unfavorable for photosynthesis. The pH in the bay ranged rom 8.2 to 8.4.

Chloride and Nitrogen

Table 32 shows the data obtained at the five most important stations in his section. The data are arranged by dates so that it is possible to trace hanges in the content of chloride and nitrogen from a point in the river to point 8.5 miles from the mouth of the river. The stations are the same s those given in Table 29 (Stations 249 and 254). Table 32 will serve also o show the differences in chloride and nitrogen on different dates. These ifferences were greatest at Station 250 because of the reversing currents f the river. Here, as at the mouth of Portage River, the number of samples as too small to show average conditions accurately. However the differences etween stations were so marked that the means given in Table 33 show clearly he relative positions of the stations with respect to abundance of chloride nd nitrogen. It will be found convenient to refer to this table to get a eneral view of the situation, and then to Table 32 for details. The upper art of Table 33 gives the means for each of the five stations on the four ates common to all; the lower part shows the means for Stations 250, 252, nd 254 on the six dates common to them.

Chloride decreased considerably from Station 249, in the river, to Sta-ion 254, far out in the lake. The most marked decrease came between Sta-ions 249 and 250. Even on August 28 and September 9, when the current was lowing outward, there was a large decrease between these stations, showing hat the water undergoes rapid dilution with water from the bay as it leaves he river. Another marked decrease took place between Stations 250 and 251, ut beyond Station 251 the decrease was slight. At Station 254 the mean as about 2 parts per million higher than the mean for the Island Section.

The nitrogen determinations in the river (Station 249) show that the ater was polluted. The abundance of unstable organic matter, as indicated y the albuminoid ammonia was much greater than in the polluted waters eported by Mason, and, of course, much greater than in the Island Section

Table 32.- Chloride and nitrogen in parts per million at stations in Maumee Bay Section, 1930

Date	Station	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3

Table 33.- Mean chloride and nitrogen in parts per million , Maumee Bay Section, 1930. Data derived from Table 32.

Station	Miles from mouth of Maumee River	No. of dates sampled	Cl as chloride	Nitrogen as			
				Free NH_3	Albuminoid NH_3	NO_2	NO_3
249	4.75 up river	4	29.9	0.618	0.708	0.048	0.10
250	-----	4	21.2	.441	.798	.006	.03
251	2.25	4	14.5	.022	.617	.002	.03
252	4.5	4	13.4	.050	.447	.002	.04
254	8.5	4	12.2	.015	.280	.002	.06
250	-----	6	20.3	.604	1.061	.007	.04
252	4.5	6	13.2	.066	.391	.002	.04
254	8.5	6	12.0	.022	.244	.002	.07

of the lake (Table 23). Free ammonia and nitrite also were high in the river, but nitrate was unexpectedly low. Just outside the mouth of the river (Station 250), free and albuminoid ammonia were still very high, but nitrite and nitrate were lower than in the river. The significance of the low concentration of nitrite and nitrate at this station, and at others farther from the river, will be taken up later. At station 251 there was a marked decline from Station 250 in all forms of nitrogen except nitrate. The decline was particularly large for free ammonia. Owing to the very high free ammonia at Station 252 on September 9, the mean value at that station was higher than at Station 251. The reason for the abundance of ammonia at Station 252 on that date is not known. Between these two stations albuminoid ammonia decreased, nitrite remained the same, and nitrate increased slightly. At Station 254 free and albuminoid were lower than at any station in the group. However, nitrite was unchanged from Station 252, and nitrate increased.

It is clear from the figures in Table 33 that the water in the river and at the mouth was polluted, and that there was marked improvement with increase distance from the river. At Station 254, which is 8.5 miles from the river, the amounts of the various forms of nitrogen were not greatly different from the means for the Island Section (Table 22). They were very much like those at Station 159, in the Portage River Section (Table 26). It may be said that the nitrogen determinations indicate a change from heavy to light pollution in a distance of 8.5 miles from the mouth of the river.

The data in Table 32 show that there were large fluctuations in the amounts of nitrogen compounds at the different stations on different dates. This is not surprising, particularly for the station at the mouth of the river because of the reversing currents. However, there is no evident relationship between the direction of current and the amount of nitrogen at Station 250. Doubtless such a relationship could be demonstrated if the direction of the current during a considerable period prior to sampling were known.

In addition to the stations listed in Table 33, four others in the Maumee Bay Section were visited. The data are shown in Table 34. Station 105 is 1.75 miles from the south shore of the lake and six miles southeast of Toldeo Harbor Light. Station 108 is three miles from Toledo Harbor Light in the same direction as Station 105. Station 233 is half a mile from the east shore of Little Cedar Point. Station 116 is 1-1/8 miles from the shore at Toledo Beach, Michigan.

It will not be necessary to dwell at length on the data from these stations. It will suffice to point out that they resemble closely those from Stations 252 and 254. The rather large differences on different dates are to be expected from the fact that currents would sometimes bring in an unusually large volume of water from sources other than Maumee Bay.

It may be instructive to introduce, at this point, some results of a sanitary survey of Maumee River made in 1898 by the Ohio State Board of Health (1899). Chemical and bacteriological samples were taken in various parts of the watershed, including the part just above the mouth. Judg-

Table 34.- Chloride and nitrogen in parts per million at special stations in the Maumee Bay Section, 1930

Station,	Date	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3
105	July 3	11.8	0.032	0.170	---	---
	August 14	12.2	.050	.307	---	---
	August 28	10.4	.012	.150	0.003	0.04
	September 9	10.2	.013	.300	.002	.06
	September 20	11.2	.012	.210	.000	.02
233	July 25	11.8	.039	.578	.001	.14
	September 20	12.6	.000	.426	.000	.04
108	August 14	11.3	.024	.250	.001	.06
116	August 16	11.8	.012	.286	.002	.06
	August 30	13.3	.006	.314	.001	.04
	September 11	14.3	.006	.432	.001	.02

ing by the results obtained, there has been a pronounced increase in pollution between 1898 and 1930, as might be expected from the increase in population. At Cherry Street bridge, which is near Station 249, the means of three samples taken in July, August, and September were as follows: free ammonia, 0.207; albuminoid ammonia 0.364; nitrite, 0.018; nitrate, 0.28 (part per million). Closely similar results were obtained for a station at Riverside Park, which is about two miles from the mouth of the river. Comparison of these results with those for Station 249 in 1930 (Table 33) shows larger amounts of all forms of nitrogen, except nitrate, for the samples of 1930. Some of this apparent increase may have resulted from a difference in dilution in the two years, but, in all probability, most of it represents a real increase in sewage pollution. The chloride content was higher, on the average, in the samples of 1898 than in those of 1930. However, this fact cannot be regarded as evidence of heavier pollution in the earlier year, for the Maumee watershed has numerous sources of saline ground waters (Ohio State Board of Healt, 1899, page 420), and the amount of inflow from such sources might vary considerably from time to time. Dole (1909, page 71) found that chloride in the Maumee at Toledo ranged from 12 to 106 parts per million in ten-day composite samples collected over a period of more than a year. Probably a number of factors, including reversing currents in the river, were responsible for the wide range. Neither of the two papers just mentioned contain data on the water of Maumee Bay.

In 1930, the water of Maumee River, and of Maumee Bay just outside of the mouth of the river (Stations 249 and 250) showed on the average, more decomposing organic matter, as indicated by albuminoid ammonia, than any other station sampled during this investigation. Free ammonia also was very high. Yet these stations were by no means as heavily polluted as some waters reported in the literature. For example, the Illinois and Michigan Canal at Lockport (carrying part of the sewage of Chicago) showed an average for the years 1896-1899 of 2.77 parts per million albuminoid ammonia, and 13.5 parts per million free ammonia. At that time, Illinois River at Averyville, about 160 miles below Chicago, contained amounts of free and albuminoid ammonia which compare favorably with those at Stations 249 and 250 (see Palmer, 1903, Tables III and XII, or Leighton, 1907, Table 63). Stations 249 and 250 showed considerably more free and albuminoid ammonia than stations in Ohio River during the same months of an earlier year (1914). Thus, at a point eleven miles below Pittsburgh, the average amounts during July, August, and September were: free ammonia, 0.376 part per million; and albuminoid ammonia, 0.313 part per million (Frost et al., 1924, Table 50). In the paper just mentioned, Ohio River was compared with other rivers in the United States and was found to be intermediate between the extremes with respect to nitrogen content. Of the rivers used for comparison, Illinois River at Joliet, immediately below the outlet of the Chicago Drainage Canal, contained the largest amount of nitrogen and this was principally in the form of organic nitrogen and free ammonia. If we make allowance for the fact that in Maumee River analysis was made for albuminoid ammonia nitrogen rather than for organic nitrogen, this river in 1930 and Illinois River at Joliet in 1921-22 appear to have been polluted to about the same degree. Maumee River, then, may be regarded as a heavily polluted river.

One of the striking features of the data from stations other than tation 249 is the small amount of nitrogen as nitrite and nitrate. At tation 250, where free and albuminoid ammonia were many times higher than n the Island Section, nitrite was only slightly higher, and nitrate was ower. This finding is contrary to expectation. In general, surface waters ontaminated by sewage have a high concentration of nitrite and nitrate as ell as of free and abluminoid ammonia. This general rule does not hold for resh sewage itself, because time is required for nitrifying bacteria to hange the free ammonia to nitrite and nitrate. Mason (1917, page 58) gave ome figures on fresh sewage at Troy, New York. Although free and albuminoid mmonia were high, there was no nitrate and only a trace of nitrite in the ewage. Low nitrite and nitrate at Station 250 cannot be explained entirely y lack of time for their formation, because at Station 249, in the river, itrite was very high, and nitrate was higher than at Station 250. Moreover, he stations farther out from the river showed little nitrite and nitrate in he presence of abundant decomposing organic matter. A possible explanation or low nitrite and nitrate at Station 250 is that the denitrifying bacteria ere unusually active in Maumee Bay, but there is no reason for assuming that hey were more active than the nitrifiers. Lack of oxygen for the process of itrification probably was not an important factor, for only at Station 249 as oxygen consistently low, and nitrite and nitrate were more abundant there han at the stations well supplied with oxygen.

The most probable explanation is one which involves the abundance of hytoplankton in Maumee Bay. On the dates in 1930 for which data are available, hytoplankton was more abundant at Station 250 than at Stations 252 and 254, nd the mean abundance at these last two stations was about six times as great s in the Island Section (Table 62). The principal factor involved in the reat production of phytoplankton at Station 250 is believed to be the high con-entration of nutritive materials in the water of the river. When the water f Maumee River enters Maumee Bay it contains an abundance of nitrogen avail-ble to plants. Free ammonia is particularly abundant because it is a natural onstituent of sewage, while nitrite and nitrate must be formed from it by he action of nitrifying bacteria. However, it is safe to assume that nitrite nd nitrate are formed in large quantities. Presumably the algae sieze upon he abundant nutritive materials and increase to such great numbers that they re able to remove almost all of the nitrite and nitrate as soon as these ompounds are formed. Free ammonia remains relatively high, possibly because t is formed more rapidly than nitrite and nitrate, or possibly because it is ess readily utilized by the algae. In either case, it seems probable that tilization of the great excess of ammonia permits the maintenance of algae n sufficiently large numbers to keep nitrite and nitrate at low concentra-ion, in spite of the fact that these compounds are formed in large amounts. ccording to this view, if it were not for the extra stimulation to growth fforded by the free ammonia, nitrite and nitrate would be much more concen-rated at Station 250 than in the Island Section.

The results at Stations 252 and 254, are in accord, on the whole, with he explanation presented above. Table 33 and Figure 18 shows that at Sta-ion 252 there was much less free and albuminoid ammonia than at Station 250, nd hence less nutritive material, both pre-formed and potential, for the algae. The algae were less than one half as abundant at Station 252 as at Station 250. To be perfectly in accord, nitrite and nitrate should be higher at Station 252, but nitrite was lower and nitrate was the same. At Station 25 free and albuminoid ammonia were reduced further, and the algae were about one third as abundant as at Station 250. Nitrate was more concentrated at Station 254 than at Station 250, although the potential supply, as indicated by the fr ammonia, was smaller. It appears that the great reduction in ammonia made it impossible to support a population of plankton algae sufficiently large to remove nitrate as completely as at Station 250. It is not clear why nitrite failed to increase along with nitrate, but in view of the complexity of the bio-chemical processes, the failure need not be considered as a major objection to the general explanation offered.

The proposed explanation for low nitrite and nitrate in this section may be used to account for a similar situation in the Portage River Section (page 93). In the section last named, conditions differed from those at Station 250 principally in the lower concentration of free and albuminoid ammonia, and this difference was reflected in the smaller number of plankton algae. In both places low nitrite and nitrate in the presence of much decomposing organic matter can be explained best by the abundance of phytoplankt

Rice (1917) studied the relation between nitrogen and plant growth in Winona Lake, Indiana, and reported conditions somewhat similar to those reported here. He found that large aquatic plants were most abundant along the shore nearest to sources of pollution, but that, at the height of the growing season, there was very little nitrite and nitrate in the water. He concluded that "in regions of very dense or even of fairly dense vegetation where great contamination exists, a chemical determination of nitrates or nitrites as an indicator of pollution in making a sanitary water analysis is absolutely worthless in itself". He believed, however, that ammonia was not used by the plants, but acted merely as reservoir from which nitrite and nitrate were derived.

Conclusions Regarding Pollution

The data on oxygen and nitrogen show that the water of Maumee River near its mouth was heavily polluted. The water of Maumee Bay also was polluted but there was marked improvement as the water moved out into the bay. At a distance of 8.5 miles from the mouth of the river, nitrogen determinations indicated light pollution, but the recovery with respect to oxygen content was more abrupt. At the mouth of the river, the oxygen content was sometimes high and sometimes low, as a result of reversing currents in the river. There were no marked oxygen withdrawals at a distance of 2.25 miles or more from the mouth of the river. A probable exception to this statement should be noted for the water immediately in contact with the bottom. Since the so-called bottom samples were taken some distance above the bottom, the maximum effect of deposited organic matter on the oxygen content would not be detected. In Maumee Bay, at the depths studied, the harmful effect of the pollution iver water appeared to be restricted to a small area near the mouth of the iver. The water of Maumee River was more heavily polluted that that of any ther tributary studied.

River Raisin Section

Oxygen, carbon dioxide, and hydrogen-ion concentration

One regular station (Station 117) in this section was visited in all hree years. Station 117 is two miles out from the mouth of River Raisin, here the depth is about 6 meters. Samples were taken on 15 dates, but not lways at both surface and bottom because the temperature was usually nearly niform. The data are given in Table 35.

The surface water was generally well supplied with oxygen, although n three occasions in 1929 it was below 90 per cent saturation. Judging by he temperature data, the water at this point is frequently mixed from top to ottom so that chemical conditions are usually almost uniform. However, on wo occasions (July 2, 1928, and June 20, 1929) there was temporary stagnaion of the lower water, resulting in considerable withdrawal of oxygen. It eems probable that at night, especially during a period of cloudy weather, he oxygen content of the water would become very low. Accordingly a sample as taken at 3:00 A.M. on July 27, 1929, following three days characterized y cloudy weather. The oxygen was lower at that time than in most of the ther samples, all of which were taken in the daytime, but the withdrawal as much less than might be expected under the circumstances. Data on free arbon dioxide and pH are lacking for June 20, 1929 but presumably that was he time of maximum free carbon dioxide and lowest pH. With minor exceptions here was a carbon dioxide deficit or only a slight excess, and the pH was .0 or above. The range of methyl orange alkalinity was about the same as ecorded for stations in the Island Section. On the basis of the data preented, the chemistry of the water at this station may be regarded as satisactory. The evidence for pollution is negative, for the few cases in which he oxygen content was low may have resulted from natural causes.

In 1930 the investigation was extended to include River Raisin at its outh and parts of the lake near the river, to determine to what extent, if ny, the lake is affected by water from the river. The last mile of the rincipal outlet of River Raisin has been canalized, and the canal walls proect a quarter of mile from the lake shore. Monroe Light is at the end of he north wall. The river current is usually very weak and reverses periodcally. Station 200 was established in the ship canal at the level of Monroe ight. Other stations were established north, south, and east of Station 200, s indicated in Table 36. The depth at these stations ranges from 3 to 6 eters and samples were always taken at a point about one meter above bottom.

Table 35.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 117 in 1928, 1929, and 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
				parts per million		per cent saturation							
		S	B	S	B	S	B	S	B	S	B	S	B
1928	June 19	19.5	19.5	--	8.5	--	92	--	-4.0	--	97	--	8.3
	July 2	23.5	19.5	10.0	6.2	116	67	-4.0	+2.0	105	105	8.5	7.7
	August 27	23.5	22	9.7	8.2	113	93	-6.9	-6.1	92	95	8.7	8.7
1929	June 20	19.7	16.7	7.6	5.5	82	56	--	--	98	91	--	--
	July 9	22.65	8.1	8.1	--	93	--	-1.5	--	95	--	8.1	--
	July 27	22.9	22.9	7.3	--	84	--	-2.2	--	98	--	8.0	--
	August 17	20.85	20.8	8.2	--	92	--	-1.0	--	93	--	8.1	--
	October 15	12.75	12.45	9.1	--	85	--	-1.8	--	98	--	8.1	--
1930	May 27	15.4	14.5	9.9	9.2	98	90	0.0	+0.5	95	93	8.2	8.1
	July 8	22.3	22.1	8.7	8.5	99	96	+0.6	+0.8	92	90	8.2	8.2
	July 30	24.3	24.3	7.9	7.9	93	93	-1.4	-1.0	94	92	8.3	8.3
	August 8	25.9	24.3	--	7.0	--	82	--	-1.4	--	94	--	8.2
	August 30	21.1	21.1	8.8	8.9	98	99	--	0.0	--	88	--	8.0
	September 11	20.4	20.35	9.1	8.8	100	97	-4.2	-3.1	91	90	8.6	8.5
	September 30	14.9	14.9	--	9.8	--	96	--	--	--	104	--	8.1

(CaCO$_3$), and pH at the mouth of River Raisin (Ship Canal at Monroe Light) and vicinity, 1930. All samples taken near the bottom. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Station	Location referred to mouth of river	Temperature	Dissolved oxygen parts per million	Dissolved oxygen per cent saturation	Free CO$_2$	Methyl orange alkalinity	pH
August 8	[1]200	Mouth of river	25.1	5.3	63	0.0	100	8.0
	202	North, ½ mile	24.6	7.3	86	-1.2	95	8.2
	215	South, ½ mile	24,9	7.6	90	-1.8	96	8.3
	211	East, ½ mile	24.9	7.3	87	-1.5	94	8.3
	213	East, 1 mile	24.9	7.2	86	-1.1	94	8.2
August 16	[1]200	Mouth of river	22.7	3.3	38	+6,3	121	7.4
	201	North, ¼ mile	22.55	8.0	91	-1.7	100	8.2
	214	South, ¼ mile	22.55	7.3	83	-1.0	102	8.1
	210	East, ¼ mile	22.5	7.7	88	-1.6	100	8.2
	213	East, 1 mile	22.55	8.7	99	-2.1	97	8.4
August 30	[1]200	Mouth of river	22.05	0.0	0	+23.5	145	7.2
	202	North, ½ mile	21.25	7.9	88	-1.5	92	8.2
	204	North, 1 mile	21.25	7.6	85	-2.1	91	8.3
	215	South, ½ mile	21.25	5.8	65	+1.3	97	7.8
	211	East, ½ mile	21.35	7.8	87	-2.6	90	8.4
	213	East, 1 mile	21.25	8.2	92	-1.0	91	8.2
September 11	[2]200	Mouth of river	20.1	9.0	98	-4.7	90	8.8
	202	North, ½ mile	20.4	3.5	38	+6.3	117	7.4
	204	North, 1 mile	20.4	8.7	96	-4.0	92	8.6
	215	South, ½ mile	20.25	9.4	103	-4.7	90	8.8
	211	East, ½ mile	20.3	9.1	100	-4.0	90	8.6
	213	East, 1 mile	20.3	9.1	100	-3.8	91	8.5

[1] Current out of river

[2] Current into river

On each of the first three dates in Table 36, the current was downriver, but the chemical conditions at Station 200 differed markedly on the three dates. There was no oxygen in the water on August 30, while on August 16 it was 38 per cent saturated, and on August 8, 63 per cent saturated. There were corresponding differences in free carbon dioxide and pH. These differences suggest that the direction of the current prior to the time of sampling is an important factor in determining the condition of the water discharged from the river. Presumably the current had been out of the river for some time before sampling on August 30, so that the outgoing water was river water undiluted by water from the lake. On August 8, it is probable that the direction of the current had just changed and the discharged water was a mixture of river and lake water That this explanation is the true one is further indicated by the fact that methyl orange alkalinity was highest when the oxygen was lowest, and lowest when oxygen was highest. In the discussion of the Maumee Bay Section it was noted that the river water was mugh higher in carbonates than the bay water. Here, too, carbonates were higher in the river than in the lake on the days when the current was outgoing, and it is reasonable to suppose that the magnitude of the difference would be a rough measure of the amount of mixing which had taken place in the volume of water being discharged at the time of sampling.

The samples taken north, south, and east of Station 200 on August 8 and 16 showed no evidence of contamination by river water. It is true that the lake water was not saturated with oxygen, but both days were cloudy and probably there was little photosynthetic activity. On August 30, the sample taken one-half mile south of the river evidently was affected by river water, as shown by the low oxygen and pH, and high free carbon dioxide as compared to other samples from the lake. It is worthy of note that this sample had higher methyl orange alkalinity than the other lake samples. August 30 was also a cloudy day, which accounts for the rather low oxygen content at the other stations in the lake.

A peculiar situation was encountered on September 11. At the time of sampling, lake water was flowing into the river, but a mass of turbid water was seen north of the river. That this turbid water had been discharged from the river is shown by the chemical determinations. Water in the mouth of the river was nearly saturated with oxygen, while at Station 202, one-half mile north, it was only 38 per cent saturated. In fact conditions at the latter station were almost identical with those at Station 200 on August 16. The river water had not reached as far north as one mile, as shown by the data for Station 204. The high content of oxygen at all stations except Station 202 is explained by the fact that the sky was cloudless, permitting the maximum activity of chlorophyll-bearing organisms.

Samples were taken at Station 200 on two dates not shown in the table, namely, July 30 and September 30. There was no current on either day. On July 30, the water was 55 per cent saturated with oxygen, and on September 30, it was 74 per cent saturated. No samples were taken in the lake near the river on these dates.

Judging by the results given in Table 36, River Raisin is not an important factor in the chemical pollution of Lake Erie. In spite of the intense pollution of the river, amounting in one case to complete exhaustion of oxygen, it is evident that the discharge is too meager to influence the lake water over a large area. This is well illustrated by the data for September 11. At the time of sampling the current had just begun to flow into the river, yet the previously discharged water, which was diverted northward by a littoral current, extended less than a mile from the river. This shows that the volume of water discharged must have been small. Obviously the river water would soon be diluted to the point where its presence could not be detected by determinations of dissolved oxygen and free carbon dioxide. Aeration and photosynthesis would aid in the process of recovery.

In 1920 a large number of determinations of dissolved oxygen were made in this region by an investigator working under the direction of Professor Jacob Reighard. The results have never been published, but Professor Reighard has made them available for inclusion in this report. Only the data of particular interest here have been used. In Table 37 are shown the data from two points in River Raisin near the mouth and in Lake Erie near the river on four dates. Unfortunately no data are available on the direction of the current at the times samples were taken.

Each sample taken in the canal at a distance of three fourths of a mile from the lake showed low oxygen content; the per cent of saturation ranged from 15.36 on August 27 to 42.06 on September 14. Samples taken here on other dates indicate that the water frequently approaches complete exhaustion of oxygen. At a distance of one fourth mile from the lake on August 27 there was less oxygen than at the point farther up the river. On September 6, oxygen was much higher at the down-river station, due, perhaps, to the fact that the current had just started to flow into the river. On the last two dates there was little difference in oxygen content at the two points. Each of the samples taken in the lake, except the one taken on September 6, showed a lower oxygen content than would be expected if the water were not contaminated by polluted river water. On September 14, oxygen was almost as low at a point one-half mile out in the lake as in the canal itself. The oxygen content in the lake on September 6 was only slightly less than in several samples taken at about the same distance from the river in 1930.

Table 38 shows data taken in the canal at Monroe Light (that is, at Station 200 of Table 36) and at three points in the lake toward the northeast. The station halfway to Stony Point is a little more than two miles from the river.

The results obtained on August 11, 12, and 13 are remarkably uniform for each station, The water at the station corresponding to Station 200 in the present investigation was about 33 per cent saturated

Table 37.- Dissolved oxygen in River Raisin Ship Canal and in Lake Erie on four dates in 1920. All samples taken at a depth of 4 feet. Data taken from an unpublished report by Professor Jacob Reighard

Sampling point	Date and oxygen content in parts per million and per cent saturation							
	August 27		September 6		September 7		September 14	
	p. p. m.	per cent	p. p. m.	per cent	p. p. m.	per cent	p. p. m.	per cent
Canal, ¾ mile from lake	1.36	15.36	1.82	19.22	2.88	30.82	3.68	42.06
Canal, ¼ mile from lake	1.07	12.08	5.22	55.77	2.93	31.35	3.98	45.02
Lake, ½ mile from Monroe Light	[1] 5.79	65.60	7.68	82.91	5.68	60.78	4.10	46.52

[1] This sample taken ¼ mile from Monroe Light

Table 38 .- Dissolved oxygen at the mouth of River Raisin (Ship Canal at Monroe Light) and at three points in Lake Erie on three dates in 1920. All samples taken at depth of 4 feet. Data taken from unpublished report by Professor Jacob Reighard

Sampling point	Date, and oxygen content in parts per million and per cent saturation					
	August 11		August 12		August 13	
	p. p. m.	per cent	p. p. m.	per cent	p. p. m.	per cent
Canal, at Monroe Light[1]	2.85	32.8	3.0	33.9	2.8	32.2
Lake, halfway to Stony Point	8.1	91.7	8.1	91.7	8.15	93.1
Lake, off Stony Point	8.0	91.4	8.0	90.6	8.15	93.1
Lake, 3 miles NE. of Stony Point	8.1	92.5	---	---	8.4	96.0

with oxygen on each date. None of the samples taken in the lake showed any evidence of contamination by river water. In each case the water was more than 90 per cent saturated.

Osburn (1926a) reported data on oxygen and pH at four stations in this area of the lake. Oxygen was high at all stations except the one three-eights mile from the river. Here the bottom water was 76 per cent saturated. The pH at these stations ranged from 7.8 to 8.2.

Chloride and nitrogen

Samples were taken at a number of stations in the River Raisin Section. Station 117, two miles off the mouth of River Raisin, was visited five times, as shown in Table 39.

One of the outstanding features of the data is the wide range between the lowest and highest values. This is particularly true of the chloride content, which ranged from 11.4 to 20.0 parts per million. This range is unexpectedly great, in view of the distance of the station from the river, and the small discharge of the river. Some of the forms of nitrogen also showed a wide range, but this is not surprising, because of the biochemical processes which go on continually. The means of the nitrogen determinations were very much like those at Station 254, in the Maumee Bay Section. These two stations also were much alike in the abundance of phytoplankton.

In addition to Station 117, several stations nearer River Raisin were visited (Table 40). The data are arranged by dates in order to facilitate comparison of the results at different stations. The table includes data from Station 117 on three dates. The results in Table 40 show some peculiarities for which explanations cannot be made on the basis of available information. Conditions in this area are highly changeable, and it would be necessary to make a much more detailed study in order to gain a knowledge of the situation with any degree of completeness. But inadequate as the data are, they have some features worthy of attention.

As at Station 117, there was a wide range in chloride content at the mouth of the river and at nearby points on different dates. On July 30, August 8, and August 16, chloride was low, while on August 30 and September 11 it was high. In itself this is not surprising because of the reversing current of the river, but it is surprising that all stations on a single date had about the same chloride content. Thus on August 8 and 16 the current was out of the river, yet the differences in chloride content at the different stations were very small. Table 36 shows that the oxygen content of the water at Station 200 was reduced, which indicates that the water was at least in part river water, and not entirely lake water which had recently entered the river. On August 30 the current was

Table 39.- Chloride and nitrogen in parts per million at Station 117, 1930

Date	Cl as chloride	Nitrogen as			
		Free NH_3	Albuminoid NH_3	NO_2	NO_3
July 8	11.4	0.003	0.133	---	0.07
July 30	11.8	.027	.280	0.002	.08
August 8	12.1	.036	.238	.000	.04
August 30	19.3	.072	.156	.004	.06
September 11	20.0	.021	.240	.003	.17
Mean	14.9	.032	.209	.002	.08

ut of the river, but the chloride content at Station 200 was lower than t five of the outlying stations. On September 11 there was a weak urrent upstream at the time of sampling, although the current had been ut and toward the north earlier, as indicated by the color of the water. et the water at Station 202, which was obviously from the river, had he lowest chloride content of any station sampled on that date.

It must be admitted that the data on chloride are perplexing; in everal cases they are contrary to expectation. That is, we should ex- ect the chloride to be higher at the mouth of the river than at the out- ying stations, particularly when the current was flowing out of the iver. One might be inclined to believe that there had been some ccidental transposition of samples or records in the laboratory, if it ere not for the fact that this could account for only a few of the nomalies.

The data on the different forms of nitrogen are more in accord ith expectation, although some unusual features are noticeable. Free mmonia was commonly very low even when accompanied by high albuminoid mmonia, as at Station 200 on August 8, 16, and 30, and at Stations 200 nd 202 on September 11. The largest amount of free ammonia was found t Station 213 on August 30, when albuminoid ammonia was relatively low. n the average, there was somewhat less than twice as much free ammonia n this section as in the Island Section. Albuminoid ammonia was higher t Station 200 than at the others, except on September 11, when the ischarged water had been deflected northward to Station 202. On the verage, there was about twice as much albuminoid ammonia in this section s in the Island Section, but on August 30, Stations 211 and 215 showed ess than the mean for the Island Section. Nitrite was consistently low, s was nitrate, except at Stations 211, 213, and 117 on September 11.

In spite of the peculiarities of the data in this section, ere is no doubt that the water of the river is polluted and that it ffects the lake water in the vicinity of the mouth. Comparisons with e data in Tables 33 and 26 show that River Raisin is less heavily olluted than Maumee River, but more heavily polluted than Portage River.

In general, free and albuminoid ammonia were higher in the iver Raisin Section than in the Island Section, while nitrite and nitrate ere lower. A similar condition has already been noted in the Portage iver and Maumee Bay Sections. It was suggested that the great abundance f plankton, resulting from the large amount of available free ammonia, as responsible for the reduction of nitrite and nitrate. The same explan- ion may be offered in the case of the River Raisin Section. At Station 17 in 1930 the phytoplankton was four times as abundant as in the sland Section (Table 62). It will be noted in Table 40 that the con- entration of free ammonia was not always great,, but almost without ex- eption the potential supply, as indicated by the albuminoid ammonia, as great. The amount present in the water is not an exact measure of

the amount available to the plankton algae, for much of it would be used as soon as it was formed.

Conclusions regarding pollution

The data on oxygen and nitrogen show that River Raisin near its mouth was polluted. Determinations of nitrogen at all stations in the lake near the river indicate that the nitrogen content had been increased as a result of the discharge of polluted river water. The most distant of these stations was two miles from the mouth of the river, but in all probability the lake water was affected for a somewhat greater distance in all directions. Marked withdrawals of oxygen definitely referable to pollution were found only at the mouth of the river and at points not more than one-half mile distant. It is probable that low oxygen occurred at greater distances in the water in immediate contact with polluted bottom. At the depths investigated the harmful effect of the polluted water apparently was restricted to a very small area near the mouth of the river. River Raisin was less heavily polluted than Maumee River, but more so than Portage River.

Detroit River Section

Oxygen, carbon dioxide, and hydrogen-ion concentration

Chemical data obtained at Station 134 in 1929 and 1930 are shown in Table 41. This station is located in the lake fully 13 miles from the mouth of the river, but it is included in the Detroit River Section because it appears to be influenced markedly by the river. The depth is 10 meters.

The data from this station may be passed over, for the most part, without comment. In many respects conditions here were very much like those found in the Island Section. However, it should be noted that carbonates were consistently low. Only one sample gave a methyl orange alkalinity in excess of 90 parts per million, whereas most of the samples in other sections of the lake were above 90. Without doubt the low methyl orange alkalinity was due to the influence of Detroit River, which was consistently low also.

Station 126 is also located in the lake, but only 5 miles from the mouth of the river. The water here is derived directly from Detroit River, except, possibly, under unusual conditions. Samples were taken here on several dates in 1928, 1929, and 1930. The data are given in Table 42.

Table 41.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at Station 134 in 1929 and 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
				parts per million		per cent saturation							
		S	B	S	B	S	B	S	B	S	B	S	B
1929	July 3	20.25	20.2	7.8	—	86	--	-0.5	—	89	—	7.9	--
	July 23	21.45	20.55	9.2	--	103	--	-1.5	—	89	--	8.1	--
	August 8	21.6	21.35	8.9	--	100	--	-1.5	--	86	—	8.1	--
	October 15	11.9	11.85	9.9	--	91	--	0.0	--	86	—	7.9	—
1930	July 8	22.3	20.4	8.5	7.4	97	81	+2.1	+3.2	86	87	8.0	7.9
	July 30	23.9	23.7	7.3	—	85	--	+0.8	+0.7	83	83	8.1	8.0
	August 18	21.6	21.2	8.2	7.9	92	88	0.0	0.0	86	86	8.1	8.1
	August 26	—	20.1	9.7	8.0	—	87	-1.4	0.0	85	87	8.3	8.0
	September 4	21.7	21.25	8.5	8.3	96	93	0.0	0.0	83	84	8.0	8.0
	September 13	--	20.35	--	7.8	--	86	--	+1.0	--	81	—	7.8
	September 30	--	16.55	--	8.9	--	90	--	0.0	--	94	—	8.1

($CaCO_3$), and pH at Station 126 in 1928, 1929, and 1930. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Year	Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
				parts per million		per cent saturation							
		S	B	S	B	S	B	S	B	S	B	S	B
1928	May 22	17	15.5	11.1	10.9	114	108	-2.0	+0.8	81	82	8.1	7.9
	June 19	18.5	18.5	8.3	8.5	88	90	-3.0	-0.5	88	88	7.9	7.9
	July 2	21	19	8.8	8.6	98	92	-3.0	-2.0	84	82	8.1	8.0
	August 28	23	22	6.3	6.3	73	71	-2.8	-2.8	86	86	8.2	8.1
1929	June 20	20.1	18.9	8.4	--	92	--	-0.5	--	86	--	7.9	--
	July 9	22.3	22.2	8.0	--	91	--	-2.0	--	93	--	8.1	--
	July 27	22.5	22.45	7.2	--	82	--	-1.2	--	86	--	7.9	--
	August 17	20.5	20.4	7.1	--	78	--	0.0	--	86	--	8.0	--
	October 15	12.35	12.05	9.4	--	87	--	-1.3	--	86	--	8.0	--
1930	May 27	13.2	12.2	9.4	9.3	89	86	+1.7	+2.2	83	83	8.2	8.2
	July 10	22.2	21.5	8.8	8.6	100	96	+1.0	+1.6	85	85	8.1	8.1
	July 23	22.9	22.8	7.9	7.9	91	91	+1.1	+1.4	86	86	8.0	8.0
	August 12	22.0	21.95	8.0	8.4	91	95	+1.0	-1.3	82	83	8.2	8.2
	August 26	20.1	20.1	8.7	8.6	95	94	+0.8	+1.1	84	85	8.2	8.2
	September 13	20.9	19.8	--	8.4	--	91	-1.3	-1.3	84	85	8.2	8.2
	September 23	18.4	18.35	--	8.5	--	90	--	-0.9	--	85	--	8.1

Because of the meager depth (7.0 meters), and the action of waves and the river current, the temperature is usually nearly uniform from surface to bottom. This condition is reflected in the chemical results, which show only minor differences between the surface and bottom samples. In general the content of oxygen was high. Of the 25 samples, more than half showed a per cent of saturation above 90, and only three showed a percentage less than 80. There was a deficiency of free carbon dioxide in most of the samples of 1928 and 1929, while in 1930 there was usually a slight excess, as previously noted for stations in the Island Section. The pH of most of the samples was 8.0 or more, and none was less than 7.9. Methyl orange alkalinity was consistently low at this station. Only one sample showed more than 90 parts per million. The sample was taken on July 9, 1929 when there was a strong southwest wind blowing. It seems probable that the wind set up a current which carried lake water from the west shore to the region of Station 126, for at the mouth of the river (Bar Point Lightship) the methyl orange alkalinity on the same day was only 84 parts per million. With the exception of the sample of July 9, the data in Table 42 may be regarded as representing conditions in water from Detroit River.

In 1930 samples were taken in the river itself at Station 219, which is located at the south end of Bois Blanc Island, near the Canadian shore of the river. The data obtained on six dates are shown in Table 43.

The data show clearly that chemical conditions at this point were satisfactory on every date that samples were taken. There was always more than 8 parts per million of dissolved oxygen, representing more than 90 per cent of saturation on at least five of the dates, and probably on the sixth also. The data are negative with regard to pollution. At this point in the river and just above it, the channel is narrow and the current is swift. As a result the water is subject to constant mixing and there is abundant opportunity for aëration.

The United States side of the river is more densely populated than the Canadian side, consequently it receives a larger amount of sewage. Also the current is more sluggish, offering less opportunity for replenishment of oxygen by contact with the air. It seemed possible, then that the water on the United States side of the lower part of the river would show a very low content of oxygen. No samples were taken on that side during the present investigation, but a few samples are available from the unpublished report by Professor Reighard. Table 44 shows the results obtained in the lake and lower river on August 13, 1920.

Table 43.- Temperature , dissolved oxygen, free carbon dioxide, methyl orange alkalinity($CaCO_3$), and pH at Station 219 in 1930. Samples taken near surface because of strong current of the river. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Date	Temperature	Dissolved Oxygen		Free CO_2	Methyl orange alkalinity	pH
		parts per million	per cent saturation			
July 10	21.5	8.8	98	+1.0	85	8.1
July 23	—	8.2	—	+0.3	84	8.0
August 12	21.3	8.1	91	0.0	83	8.0
August 26	20.45	8.5	94	-0.5	84	8.1
September 13	20.1	8.5	93	-0.4	85	8.1
September 23	18.4	9.0	95	0.0	84	8.0

Table 44.- Dissolved oxygen at several points in the Detroit River Section on August 13, 1920. All samples taken at depth of 4 feet. Data taken from an unpublished report by Professor Jacob Reighard

Sampling point	Dissolved oxygen	
	parts per million	per cent saturation
Lake, off Pointe Mouillée Club House	5.7	65.1
Lake, off mouth of Huron River	7.15	80.9
Detroit River, 3 miles north of preceding	7.5	84.9
Detroit River, between Grosse Isle and Bois Blanc Isl.	8.05	90.0
Detroit River, head of Bois Blanc Isl.	8.10	91.7
Lake, at Detroit River Light	8.15	92.3

The water was rather low in oxygen at the station near Pointe Mouillee. The cause of this condition is not evident. It seems improbable that the water was derived from Detroit River, for the stations above Pointe Mouillee contained much more oxygen. It might be supposed that the water came from Huron River, but the few data obtained by the Michigan Stream Control Commission in 1931 (unpublished) do not indicate an oxygen deficiency in the lower part of the river. However, not enough samples were taken in the river to justify the conclusion that it could not be responsible for the condition noted off Pointe Mouillee. The presence of water higher in oxygen at the station nearer the mouth of the river is not an insurmountable objection to this explanation, for the river is subject to reversals of current near the mouth. A change from outgoing to ingoing current may have taken place just before the sample was taken near the mouth of the river, so that the water at that point would be from Detroit River rather than from Huron River. That such a situation actually existed is suggested by the fact that the amount of oxygen at the point off the river was almost the same as in Detroit River three miles above. The amount of oxygen at a point between Grosse Isle and Bois Blanc Island was noticeably greater than at the two proceding points, which are closer to the west shore of the river. However, the evidence is too scanty to justify the conclusion that the observed condition near the west shore is the usual one or that the condition resulted from pollution.

The water of Lake St. Clair enters Detroit River with a high content of dissolved oxygen. This is well shown by results obtained at the intake for the Detroit water supply (Detroit Department of Water Supply, 1930). Over a period of a year from July, 1929 to June, 1930, the lowest observed value was 9.0 parts per million in June, 1930, and the mean was 11.7 parts per million, which would be near the saturation point. Additional data on chemical conditions in Detroit River are given in Table 45. On September 23, 1930, a series of six samples was taken along a line from the south end of Lake St. Clair to Station 126, in Lake Erie near the mouth of Detroit River. The sampling points near Belle Isle, Ambassador Bridge, and Fighting Island were in mid-stream. No claim is made that samples from these points give an adequate idea of conditions in cross-sections of the river. They were taken incidentally during an excursion to Lake St. Clair for plankton samples, and represent conditions only at the time and place indicated.

There was an abundance of oxygen at all of the stations listed in the table. The sky was overcast during the entire period of sampling and it is reasonable to suppose that higher results would have been

Table 45.- Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at several stations in and near Detroit River on September 23, 1930. All samples taken well below the surface. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Sampling point	Temperature	Dissolved oxygen		Free CO_2	Methyl orange alkalinity	pH
		parts per million	per cent saturation			
Lake St. Clair	18.4	8.7	92	-0.9	83	8.0
Opposite Belle Isle	18.45	8.8	93	-1.3	82	8.1
Under Ambassador Bridge	18.2	8.8	93	0.0	83	8.0
Opposite Fighting Island	18.1	8.8	92	0.0	83	8.0
Station 219	18.4	9.0	95	0.0	84	8.0
Station 126	18.4	8.5	90	-0.9	85	8.1

obtained had the sky been clear. Certainly the data show no evidence of pollution. However, it should not be assumed that all parts of the river would show the same satisfactory results. Sewage enters the river near the shore and there is a decided tendency for it to cling to the shore as it moves down stream. At the level of Ambassador Bridge and Fighting Island there would be little mixing of sewage and river water, so that the observed results in mid-stream are not surprising, but one would expect to find definite evidence of pollution along shore.

Below Fighting Island little sewage enters the river, and there is abundant opportunity for dilution of the sewage received farther up river. For that reason it seems probable that the results obtained at Station 126 (Table 42) are fairly representative of Detroit River water at the mouth. Conditions at Station 219, near the Canadian shore, were similar to those at Station 126 on the same dates of 1930. As stated before, the United States side of the river receives more sewage than the Canadian side, and also has a more sluggish current in the lower part of the river. But if these circumstances give rise to unfavorable chemical conditions in any considerable part of the water below Grosse Isle, one would expect to find evidence of it at Station 126, because of its position, which is nearer the west shore than to the east shore. Failure to find such evidence is doubtless due, principally, to great dilution of the sewage. Contact with the air would aid in recovering any oxygen lost, but photosynthesis must play a relatively minor part because of the scarcity of phytoplankton in the river.

The literature on pollution of streams contains many examples of complete or almost complete exhaustion of oxygen. Wiebe (1928) in his study of the upper Mississippi, reported several stations within and below Minneapolis and St. Paul which had little or no oxygen in August, 1926. The explanation of the difference in the amount of oxygen there and in lower Detroit River is to be found in the relative capacity for dilution. In August, 1926, the discharge of Mississippi River at St. Paul was 2,810 cubic feed per second, and the discharge of Detroit River in August, 1930, was roughly 202,000 cubic feet per second. The combined population of Minneapolis, St. Paul, and South St. Paul in 1930 was 745,971, and the combined population of cities contributing sewage directly to Detroit River in 1930 was 1,850,340. Assuming that the per capita output of sewage was the same in the two regions, dilution in Detroit River would have been roughly 29 times as great as in Mississippi River. The importance of dilution is shown by the fact that in September, when the discharge of the river had increased to 8,630 cubic feet per second, Wiebe found that the amount of oxygen at the badly polluted stations increased tremendously. For example, at a point just below the Twin Cities, there was no oxygen on five consecutive days in mid-August. On the same days of September, there was an average of

5.95 parts per million. Some of this increase was due to a lowering of the water temperature and consequent greater solubility of oxygen, but, in all probability, increased dilution was the principal factor involved.

Chloride and nitrogen

Samples were taken on six dates at each of three stations in this section (Table 46). Station 219 is in Detroit River at the south end of Bois Blanc Island, near the Canadian shore. Station 126 is in Lake Erie, 5 miles from the mouth of the river. Station 134 is also in Lake Erie and is 13 miles from the mouth of the river.

The chloride content of the water in this section varied considerably on the different dates. This is particularly noticeable at Station 126, where it ranged from 6.1 to 13.6 parts per million. Comparing Stations 219 and 126 on the same dates, it may be seen that they were not in agreement; the lowest value was recorded for Station 219 on the same day as the highest for Station 126. The mean chloride at Station 134 was lower than at Station 126, although the opposite relationship is to be expected, because of the high chloride content in the other sections of the lake. Obviously Station 134 must receive Detroit River water which has undergone little or no mixture with water from the open lake. The lack of agreement between Stations 134 and 126 is not surprising in view of the large variations in this section. It merely means that too few samples were taken to show the average chloride content accurately.

The different forms of nitrogen show a rather wide range also, particularly free ammonia. Yet the means at the bottom of the table have some characteristics in common which are markedly different from those at stations near the mouths of other rivers. In spite of the small number of samples, it seems probable that the means are a fairly reliable index of the character of the water with respect to the concentration of nitrogen compounds. Comparison of Station 126 with Station 250 (Table 33) shows that Station 126 was much lower in free and albuminoid ammonia, somewhat lower in nitrite, but higher in nitrate. The results at Station 126 agree more closely with those at Station 254 (Table 33), Station 159 (Table 26), and Station 117 (Table 39). Still closer agreement is to be found between Station 126 and the mean of stations in the Island Section (Table 22). Of particular interest is the fact that the amount of decomposing organic matter, as indicated by albuminoid ammonia, was greater at Station 126 than in the Island Section.

and 134 (Detroit River Section), 1956

Station	Date	Cl as chloride	Nitrogen as			
			Free NH_3	Albuminoid NH_3	NO_2	NO_3
219	July 10	7.9	0.009	0.122	0.003	0.12
	July 23	7.5	.018	.218	.001	---
	August 12	4.8	.024	.135	.002	.10
	August 26	6.2	.006	.082	.002	.08
	September 13	6.2	.018	.120	.004	.20
	September 23	7.0	.009	.072	.001	.10
126	July 10	7.0	.005	.100	.003	---
	July 23	6.1	.026	.199	.002	---
	August 12	13.6	.066	.130	.004	.10
	August 26	6.8	.009	.105	.004	.12
	September 13	8.8	.023	.126	.004	.25
	September 23	9.3	.030	.079	.003	.09
134	July 8	8.6	.027	.101	---	.14
	July 30	7.8	.015	.152	.002	.14
	August 18	6.4	.015	.110	.002	.14
	August 26	4.4	.012	.116	.004	.10
	September 4	5.8	.006	.093	.001	.10
	September 13	5.5	.032	.120	.004	.12
219	Mean, six dates	6.6	.014	.125	.002	.10
126	Mean, six dates	8.6	.026	.123	.003	.14
134	Mean, six dates	6.4	.018	.115	.003	.12

It should be noted that the amount of nitrate at Station 126 was higher than at stations near the other rivers, in spite of a much smaller amount of albuminoid ammonia. Nitrite also was somewhat more abundant than at such stations, other than Station 250. This tends to confirm the suggested explanation for the low nitrite and nitrate in the presence of an abundance of free and albuminoid ammonia observed at stations near Portage, Maumee, and Raisin Rivers. It was suggested that the large amount of phytoplankton at these stations resulted in almost complete withdrawal of nitrite and nitrate as soon as these compounds were formed from ammonia. Reference to Table 62 shows that phytoplankton was rare at Station 126 in 1930; it was only 1/26 as abundant as at Stations 252 and 254. Consequently there was slight demand upon the nitrite and nitrate, and these compounds could accumulate in the water.

In order to gain some idea of the effect of sewage entering Detroit River, a special series of samples was taken on September 23, as shown in Table 47. The first sample was taken in Lake St. Clair near its outlet, and progressing downstream, others were taken in mid-stream at Belle Isle, Ambassador Bridge, and Fighting Island. Finally samples were taken at Stations 219 and 126. If sewage has a marked influence on the content of chloride and nitrogen of the river we should expect such a series of samples to show it.

The nitrogen determinations, in general, do not show a consistent increase in the down-river samples over those up-river. Free ammonia was lowest in Lake St. Clair and highest at Station 126, but it decreased rather than increased in the river itself. Albuminoid ammonia was higher in Lake St. Clair than at Station 126. Nitrite was the same at all stations above Station 126, and increased only slightly at the latter. Nitrate was about the same at all stations. The data in this single series of samples, are not consistent with the idea that sewage pollution in Detroit River has a pronounced influence on the concentration of nitrogen compounds in the water.

Further evidence on this point may be gained by examination of some results on the water of Detroit River near its source in 1901 (Detroit Board of Health, 1902, page 64). The mean values (in parts per million) for July, August, and September of that year were as follows: free ammonia, 0.011; albuminoid ammonia, 0.093; nitrite, none; nitrate, 0.12. Comparison of these figures with the means for the same period of 1930 at Stations 219, 126, and 134 (Table 46) shows that the latter are somewhat higher, with two minor exceptions. However, the differences are not great, and they hardly can be regarded as definite evidence of

Table 47.- Chloride and nitrogen at several stations in and near Detroit River on September 23, 1930

Sampling point	Cl as chloride	Nitrogen as			
		Free NH_3	Albuminoid NH_3	NO_2	NO_3
Lake St. Clair	2.4	0.006	0.094	0.001	0.09
Opposite Belle Isle	2.8	.015	.078	.001	.09
Under Ambassador Bridge	2.8	.012	.090	.001	.10
Opposite Fighting Island	2.9	.012	.071	.001	.10
Station 219	7.0	.009	.072	.001	.10
Station 126	9.3	.030	.079	.003	.09

polution. In this connection it may be pointed out again that Frost, et al. (1924) found no undoubted effect of the sewage of Cincinnati on the nitrogen content of Ohio River when the discharge exceeded 50,000 second-feet, that is, when the number of contributing persons per second-foot was approximately the same as in Detroit River. Obviously the failure to find definite evidence of pollution in the analyses for nitrogen near the mouth of Detroit River is explained by the great excess of river water over sewage.

In view of the slight evidence of increase in nitrogen in Detroit River, what explanation can be offered for the sharp increase in chloride in the lower river (Table 47)? This increase is believed to be due in large part to natural causes. There are no available data on the chloride content of the lower river before the river became subject to pollution, but, as pointed out on page 228, there are numerous sources of saline ground waters in this region, particularly on Grosse Isle, and in the rocks underlying the Livingstone channel. While it is not possible to determine how much of the increase was due to natural causes and how much to pollution, in the light of the data on nitrogen, it seems not unreasonable that most of it should be assigned to natural causes. This statement should be qualified by saying that some may have been derived from wastes of salt works on the bank of the river, but it is not probable that much of it came from domestic sewage. The large variations shown in Table 46 may be explained on the basis of incomplete mixing of the incoming saline waters with the water of the river.

Conclusions regarding pollution

Although Detroit River receives sewage from municipalities aggregating nearly two million persons, determinations of oxygen and nitrogen near the mouth of the river yield no definite evidence of pollution. The explanation for this fact lies in the great volume of discharge of the river in relation to the number of persons contributing sewage. Doubtless the nitrogen content of the river has been increased as a result of pollution, but in all probability the increase has been too small to have an appreciable effect on the oxygen content of the water (with the probable exception of water immediately in contact with polluted bottom). The reductions in oxygen content noted at Station 126 (Table 42) probably resulted principally from natural causes. It may be concluded that, at the depths studied, pollution in Detroit River has had no harmful chemical effect on the water of Western Lake Erie.

Chemical conditions
near the west shore in winter

During the warm months of the year decomposition of organic matter in the water proceeds at a high rate, and dissolved oxygen is rapidly consumed. But the water is exposed to the air, and as it is churned by waves and currents, there is abundant opportunity to replenish the supply of oxygen. Algae are commonly abundant at this time of year, and in the presence of sunlight they aid materially in maintaining a high oxygen content. During the winter months, low temperature retards the process of decomposition, and there is less demand on the supply of oxygen. However, the water is covered with a layer of ice which prevents interchange of gases with the air. The ice is frequently covered with a blanket of snow preventing free entrance of sunlight, and the amount of both sunlight and phytoplankton are usually reduced in winter. Hence photosynthesis is not as important a factor in maintaining the supply of oxygen as in summer. It appeared possible, then, that the water of Western Lake Erie might become very low in oxygen during the winter. Accordingly, samples were taken at four stations near the west shore of the lake in February, 1930. A list of the stations, with their location and other pertinent data are given below:

Station A. Located 2 miles southeast of the shore at Stony Creek, and roughly 1 mile from Stony Point. Depth, 6.1 meters. Samples taken at surface and bottom on February 5. Ice 8.5 inches thick, with little snow on the ice. Sky cloudy. Water clear.

Station B. Located 1 mile east of Monroe Light at the mouth of River Raisin. This station is near Station 213 as shown in Table 36 Depth, 5.3 meters. Samples taken at surface and bottom on February 7. Ice 8 inches thick, with snow distributed in patches, covering perhaps one half the surface. Sky cloudy. Water clear.

Station C. Located in La Plaisance Bay, 2.5 miles southeast of pier at Bolles Harbor. Depth, 4.7 meters. Samples taken at surface and bottom on February 5. The bottom sample for oxygen was lost later by freezing. Ice 10 inches thick. Snowing heavily. Water clear.

Station D. Located 3 miles roughly ESE of the shore at Lakeside, Michigan. This station is about 3.75 miles from Toledo Harbor Light. Depth, 5 meters. Samples taken at surface and bottom on February 7. Ice 14 inches thick. Snow distributed in patches. Sky cloudy. Water turbid.

The chemical data are shown in Table 48.

Chemical conditions at the different stations were remarkably uniform. The oxygen content was unexpectly high; it ranged from 10.4 to 12.1 parts per million, and from 73 to 83 per cent of saturation. The actual amount of oxygen present was thus greater than in any of the summer samples taken in this region, and the lowest per cent of saturation was not greatly lower than in many of the summer samples. There was an excess of free carbon dioxide in every sample, but the excess was small, and pH did not fall below 7.5.

Table 48.– Temperature, dissolved oxygen, free carbon dioxide, methyl orange alkalinity ($CaCO_3$), and pH at four stations near the west shore of the lake in winter, under the ice. See text for location of stations. Temperature in degrees centigrade; chemical data, where possible, in parts per million

Station	Date	Temperature		Dissolved oxygen				Free CO_2		Methyl orange alkalinity		pH	
				parts per million		per cent saturation							
		S	B	S	B	S	B	S	B	S	B	S	B
A	Feb. 5, 1930	0.4	0.4	10.5	10.5	73	73	+1.4	+1.4	96	96	7.6	7.6
B	Feb. 7, 1930	0.5	0.75	11.0	11.1	76	78	+1.0	+1.4	91	94	7.6	7.6
C	Feb. 5, 1930	0.2	0.55	12.1	—	83	—	+0.5	+1.4	96	101	7.7	7.6
D	Feb. 7, 1930	0.2	0.95	11.0	10.4	76	73	+1.9	+2.4	79	85	7.5	7.5

It is evident from these results that chemical conditions under the ice as late as the first week in February were far from any point which could be regarded as unfavorable to life in the water. The winter of 1929-1930 was somewhat abnormal in that the months of November and December, 1929, and January, 1930, were slightly colder than normal, while February, 1930, was decidedly warmer than normal. As a result the ice formed a few days earlier, and disappeared many days earlier than usual. Judging by the rather incomplete information given in the Snow and Ice Bulletins of the United States Weather Bureau, ice formed on the lake about December 15 and disappeared about February 24, so that the samples were taken when the closed period was three fourths completed. It seems improbable that the chemical conditions changed radically in the few days remaining before disappearance of the ice.

The chemical data obtained under the ice in February, 1930 leave a number of questions regarding pollution unanswered. During the summer of the same year, it was found that marked oxygen withdrawals were limited to relatively small areas near the mouths of Maumee and Raisin Rivers. With reduced opportunity for recovery by aëration and photo-synthesis under the ice, a general outward extension of these areas would be expected. However, the results at Station B, one mile from the mouth of River Raisin, indicate, that the extension of this region was not great, and probably the same was true for Maumee Bay, although Station D is too far from the river to be of value as an index. As far as the data go, they indicate that chemical conditions under the ice were little, if any, less favorable than those prevailing during the open period. Normally, navigation is closed in this general region for a period of 90 days, or almost three weeks longer than in the winter of 1929-30. Whether a closed period of that length or longer would be accompanied by a large reduction in oxygen at the stations sampled remains open to some question. It seems unlikely that the actual amount of oxygen would be reduced below the amount present during the summer, although the per cent of saturation might be reduced considerably. On the whole the data do not indicate the need for revision of the conclusions regarding pollution based on the samples taken in the summer.

Evidence of poisons in the water

Industrial centers, such as Detroit and Toledo, are sources of large amounts of trade wastes which enter the tributary streams and finally reach Lake Erie. In this investigation, no attempt was made to analyse the water for any of the large number of substances of poisonous nature which might be present. Obviously the magnitude of such a task precluded the possibility of doing it justice in a general survey of this kind. It may be assumed that poisonous substances are present in the water; the question to be decided is whether they are present in sufficient concentration to injure or kill the plants and animals in the lake. The answer to this question must be given largely on the basis of indirect evidence.

The absence of strong acids or alkalies in appreciable quantities is indicated by the close correlation between the amount of dissolved oxygen and the excess or deficiency of free carbon dioxide in the water, even near the mouths of the rivers. That is, the degree of acidity or alkalinity to phenolphthalein was such as might be expected from the oxygen content of the same sample, knowing that low oxygen is ordinarily associated with an excess, and high oxygen with a deficiency, of free carbon dioxide. Moreover pH values were never extremely high or extremely low.

However, data on acidity or alkalinity would give no clue to the presence of neutral chemicals or those with weakly acid or basic properties which might be highly toxic to living organisms. Phenol and some of its derivatives are common industrial wastes of this type. Fortunately published data on the amount of phenols in parts of Western Lake Erie are available (Donaldson and Furman, 1927). This paper reports 210 tests made at four stations, three near Toledo Harbor Light and one near the mouth of Detroit River. Phenol was detected in 86 of the 210 samples. The maximum amount in any one sample was 52 parts per billion; the mean at Toledo Harbor Light was 3.6, and at the mouth of Detroit River 7.9 parts per billion. Numerous analyses were made of wastes which enter Maumee River and its tributary streams at Toledo. The waste showing the highest concentration of phenol contained 37,800 parts per billion (0.0038 per cent). Baskina (1926) reported that Cyclops insignis was unharmed by solutions of phenol weaker than 1/200 Normal (0.047 per cent), which is more than ten times as strong as the waste indicated above. If we take into account the great dilution which the wastes undergo in the river and in Maumee Bay, it seems highly improbable that concentrations sufficient to be harmful to the most delicate plankton organisms would ever occur in the bay or lake.

It is possible that chemicals other than phenols are present in concentrations great enough to be harmful to organisms, but the possibility seems remote. The best indirect evidence on this point is afforded by the data on abundance of plankton in different sections of the lake. If poisonous substances kill the plankton organisms, we should expect to find little plankton where there is definite evidence of pollution, as in the Maumee Bay Section. Contrary to such expectation, the water of this section contained much more plankton, both plant and animal, than the water of the Island Section. In fact, throughout the area studied, the more heavily polluted stations yielded a greater abundance of plankton than the stations polluted only lightly. Obviously, then, in the polluted areas, the factors making for great production of plankton were more effective than any possible factors tending toward destruction of plankton.

The possible effect of poisonous chemicals on the fishes of the lake will be considered in later pages (page 303).

Chloride content of Lake Erie

The amount of chlorine as chloride in Lake Erie is high as compared with the upper lakes. According to analyses reported by Dole (1909), the mean for Lake Erie at Buffalo in 1906-1907 was 8.7 parts per million, as compared with 1.1 for Lake Superior, 2.7 for Lake Michigan, and 2.6 for Lake Huron. The mean for the Island Section of Lake Erie in July, August, and September, 1930, was 10.3, which agrees closely with the mean at Cleveland for the same months of 1910-1911 as reported by Jackson (1912).

Domestic sewage and certain kinds of trade wastes contain much sodium chloride, and when the normal content of a lake is known, chloride is a valuable index of the degree of pollution. Jackson (1912, page 43) stated that the high chloride at Cleveland had no sanitary significance because of the inflow of salt from salt works and natural deposits. A review of the literature leaves no doubt that Jackson's conclusion should apply to the lake as a whole. References of special value in this connection are: Sherzer (1900 and 1913), Kellogg (1917, p. 204 and 1925, p. 48), Fuller (1905), Ohio State Board of Health (1899), Foulk (1925).

The phytoplankton of Western Lake Erie.

Introduction

Previous investigations in the Great Lakes[5]

The earliest investigations of the algae and protozoa of the Great Lakes were made on material obtained from municipal water supplies. By taking samples from the tap-water periodically, it was possible to follow seasonal changes in the plankton of the lakes.

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[5] The large aquatic plants were not studied. The following papers on large aquatics of the Great Lakes were encountered in the literature: Campbell (1886) Pieters (1894 and 1901), Thompson (1896), Moseley (1899), Pond (1905), MacClement (1915), Klugh (1915), and Muenscher (1929 and 1932). See also Miller's bibliography of Ohio botany (Miller, 1933).

The plankton algae and protozoa of Lake Erie have been studied in greater detail than those of the other lakes. Kellicott (1878) noted the seasonal distribution of a number of algae in the water supply of Buffalo. Mills (1882) studied the forms from the same source, and took samples from Niagara River also. Vorce (1880) noted the changes in the kinds and abundance of diatoms in the water supply of Cleveland throughout the year. In later papers (Vorce, 1881 and 1882), he listed and illustrated a large number of forms from the water supply. Some years later the algae at the west end of the lake were studied in considerable detail by Pieters (1901), Riddle (1902), and Snow (1903). Jennings (1900), Landacre (1908), Walton (1915), and Stehle (1923) studied the protozoans of the same region. Burkholder (1929a) listed the algae, protozoa, and rotifers of eastern Lake Erie. Tiffany and Ahlstrom (1931) described some new forms from the region of Put-in-Bay. A more extended account of the algae of this region may be found in a paper by Tiffany (1933).

Papers on the algae and protozoa of Lake Michigan have been written by Briggs (1872), Thomas and Chase (1887), Thompson (1896), Kofoid (1896), Leighton (1907), and Eddy (1927). Eddy's paper is especially valuable because it contains reviews of the earlier papers. Apparently there have been no taxonomic studies of these groups in Lake Superior and Lake Ontario. However, Burkholder and Tressler (1932) listed the genera of algae taken in four bays near the outlet of Lake Ontario. Pieters (1894) listed the algae of Lake St. Clair; Klugh (1913), MacClement (1915), and Bailey and Mackay (1921) listed those of Georgian Bay in Lake Huron.

Reighard (1893) was the first to make a quantitative study of the plankton of the Great Lakes. In the spring of 1893 he made a number of collections with a horizontally hauled net in Lake Michigan and Detroit River. The results need not be discussed here, but it may be mentioned that he found very little plankton in Detroit River.

In September of the same year Reighard and his associates made a study of the plankton in Lake St. Clair and in the western part of Lake Erie (Reighard, 1894 and 1894a). Samples were taken with a net of the Hensen type, and the amount of plankton was determined volumetrically. Of the 21 plankton stations, three were in Lake Erie: two near the islands and one some distance south and east of the mouth of Detroit River. The mean volume of plankton in Lake St. Clair, expressed in cubic centimeters per cubic meter of water, was 3.03. The mean volume for the 2 stations near the islands in Lake Erie was 8.98 cubic centimeters per cubic meter. Only 1.14 cubic centimeters per cubic meter were found at the station near the mouth of Detroit River. The general conclusions reached by Reighard may be summarized briefly in his own words: "(1) The volume of plankton in Lake St. Clair is relatively small. (2) The plankton is distributed over Lake St. Clair with great uniformity. (3) There is much more plankton in the surface stratum of water than in any deeper layer of equal volume. (4) There is about three times as much plankton in Lake Erie in the neighborhood of Put-in-Bay Islands, as in Lake St. Clair."

In 1894, Ward and his associates made a study of the plankton of Lake Michigan in the Traverse Bay region. (Ward, 1895 and 1896). The methods employed were almost identical with those employed by Reighard in Lake St. Clair. Ward found that the mean volume of plankton at 18 stations was 3.69 cubic centimeters per cubic meter. This amount was not far different from the mean for Lake St. Clair as reported by Reighard. However, Ward pointed out that the mean volume for hauls in Lake Michigan at depths similar to those in Lake St. Clair (1.5 to 5.6 meters) was 6.39 cubic centimeters per cubic meter, or more than twice the mean for Lake St. Clair. In Lake Michigan the total amount of plankton increased with greater depth, but the amount per unit volume decreased. There was no evidence of swarms of the total plankton. Investigation of vertical distribution showed that the volume of plankton per unit volume of water was much greater in the upper two meters than in lower strata. The deepest stratum was almost devoid of plankton.

In 1898 the United States Fish Commission established a biological laboratory at Put-in-Bay, Ohio (Smith, 1898). The laboratory was under the direction of Professor J. E. Reighard, and a number of other investigators were on the staff. For a brief account of the work carried on here, the reader may refer to the reports of the Commissioner of Fish and Fisheries for the years ending June 30, 1899, 1900, 1901 and 1902. Some quantitative studies of the plankton were made, but the results have never appeared in print. It was almost 30 years before another party of investigators undertook a quantitative study of the plankton of the Great Lakes.

In the meantime the only quantitative results published were those of Whipple (Leighton, 1907) in Lake Michigan at Chicago; Stehle (1923) on the protozoa of the surface waters near Put-in-Bay; and Eddy (1927) on the littoral plankton of the southern part of Lake Michigan. Whipple's results were too fragmentary to justify discussion here. Stehle counted the plankton protozoa in measured samples of surface water taken in the harbor of Put-in-Bay, in Terwilliger's Pond, and in the open lake. Only 18 forms were taken in the open lake and their abundance was never great. The largest count of any one form was 145 per liter and most of the counts were much lower. Eddy's paper is based on surface collections made near shore in the southern part of Lake Michigan. Diatoms were predominant in the plankton at all times, and the same species were always conspicuous. Comparison of recent collections with those made forty years before showed essentially the same kind of plankton in both periods.

The most extensive study of the phytoplankton of the Great Lakes was the one carried on in Lake Erie in 1928 and 1929 as reported by Burkholder (1929a and an unpublished manuscript). In 1928 work was confined to the area east of Long Point, but in 1929 all of the lake east of Western Lake Erie was covered. Samples were taken by the pump method; 50 liters were pumped from the desired depth, emptied into a metal container, and strained through a plankton net. Additional one liter samples were run through a continuous-flow centrifuge to obtain the nannoplankton organisms. In later pages the results obtained will be compared with those obtained in the present investigation.

Another recent study is that of Gottschall (1930) on the plankton of the water supply at Erie, Pennsylvania. Finally, may be mentioned the work of Burkholder and Tressler (1932) on some bays at the east end of Lake Ontario. Both of these reports will be considered briefly later.

Materials and methods

This report is based entirely on samples of water from which the plankton was removed by a Foerst continuous-flow electric centrifuge like the smaller of the two described by Juday (1926). In 1929, 185 samples were taken, and these were grouped into 110 series, all samples taken at a station on the same day constituting a series. At the shallow stations, only single samples were taken. In 1930, 287 samples in 115 series were taken. The stations visited were the regular stations shown in Figure 1, and a few special ones which will be noted in the text.

Samples of water were taken from the lake with a Kemmerer-Foerst water bottle similar to the one described by Birge (1922). The size of the sample was commonly three liters, and was never less than 1.5 liters, the capacity of the bottle. In 1929, the routine procedure was to take two samples at each of the deeper stations: one at the surface and another about one meter above bottom. In 1930, samples at one or two intermediate depths in addition were taken at all except the very shallow stations. Thus, at Station 37A samples were taken regularly at 0, 4, 8, and 13 meters depth. From these data it is possible to compare the mean number of organisms determined by samples from four depths with that determined by samples from only the surface and bottom. Tables 49 and 50 were designed to facilitate such a comparison. For each of the genera shown, the mean number per liter for the station was first determined from two (surface and bottom) samples, and then from all of the four samples.

A comparison of the pairs of means in the tables shows that some agree closely and that in every case the individuals of a pair are of the same order of magnitude. That is, in no case does one mean show great abundance and the other great scarcity. The conclusions drawn from the data would have been the same, whether the mean was based on four samples or two samples. If these data from Station 37A are representative of the entire area studied and of both years, it may be concluded that the data of 1929 are as valid as those of 1930 for the purposes of this investigation. The data in Tables 49 and 50 show the adequacy of series of two samples as compared with those of four samples, but not the adequacy of the series of four samples themselves. However, if the algae are so distributed that samples taken at 0 and 13 meters give essentially the same mean as samples taken at 0, 4, 8, and 13 meters, it is highly improbable that a further reduction in the interval between sampling points would change the result materially.

In the laboratory, a measured sample of the sample from the lake was run through the centrifuge. The size of this centrifuge sample was usually one liter, but sometimes smaller or larger samples were used, depending on the abundance of plankton. The plankton was transferred from the centrifuge bowl to a vial and made up to a known volume, usually 25 cubic centimeters.

The Sedgwick-Rafter method of counting was used. The counting cell had a depth of one millimeter, and the tube length of the microscope was adjusted so that the Whipple micrometer covered one square millimeter of the cell. Ten squares in each of two cells (20 squares in all) were counted, and the count converted to the number of organisms per liter of lake water. With routine procedure, that is, with a centrifuged sample of one liter concentrated to 25 cubic centimeters, the conversion factor was 1,250. With other sizes of sample and concentrate the factor was as low as 625 and as high as 2,500. It must be evident that, with such conversion factors, statements of the number of organisms per liter in units of smaller size than a thousand would indicate an accuracy which the data do not possess. For that reason figures in tables have been rounded off to the nearest thousand, except those showing general averages which fall below one thousand. These are shown in smaller units

Table 49.- Comparison of the mean number of certain diatoms at Station 37A on five dates in 1930 as determined by samples taken at two depths, with the mean number determined by samples taken at four depths. Abundance in thousands of units per liter.

Plankton	Date, and number of samples used to determine mean									
	April 21		May 7		May 21		September 19		October 2	
	2	4	2	4	2	4	2	4	2	4
Melosira	12	10	6	13	42	33	35	33	32	24
Stephanodiscus	6	8	8	6	10	6	221	225	79	66
Tabellaria	10	8	1	12	10	14	2	2	8	6
Fragilaria	4	4	6	7	14	10	2	3	25	21
Synedra	17	19	12	14	18	14	0	1	8	5
Asterionella	9	8	16	24	20	17	20	20	17	14
Total	58	57	49	76	114	94	280	284	169	136

Table 50.- Comparison of the mean number of certain green and blue-green algae at Station 37A on four dates in 1930 as determined by samples taken at two depths, with the mean number determined by samples taken at four depths. Abundance in thousands of units per liter.

Plankton	Date, and number of samples used to determine mean							
	August 5		September 6		September 19		October 2	
	2	4	2	4	2	4	2	4
Westella	11	13	7	8	30	35	32	37
Coelastrum	18	18	10	7	20	17	1	2
Merismopedia	11	9	40	23	15	14	66	58
Coelosphaerium	18	19	6	5	16	12	35	24
Microcystis	7	9	27	30	306	320	126	140
Oscillatoria	2	4	2	2	32	31	24	24
Total	67	72	92	75	419	429	284	285

to emphasize their rarity.

No attempt was made to determine the precision of the counting method. Whipple (1927, p. 101) stated that two examinations of the same sample by the Sedgwick-Rafter method seldom differ by more than 10 per cent. Allen (1921) made a statistical study of his method of enumerating marine algae, but did not describe the method in detail. He found that the mean deviation from the mean of several counts of the same sample could be kept within 10 per cent. This indicates a precision of about one half that reported by Whipple. Allen concluded that errors in counting were less important than those arising from inadequate mixing of the sample before transfer to the counting slide.

Many published records of phytoplankton counts have lost much of their value through a failure of the authors to record the units used in counting the various algae. Some algae appear as small individual cells while others appear as great filaments or colonies. With the ordinary method of enumeration each kind is given equal weight regardless of size. In an attempt to avoid this difficulty, Whipple devised a method of counting on the basis of standard units of area or volume (see Whipple, 1927, p. 124). This method has been used widely by students of sanitation, but not by limnologists in general. The principal drawback to the method is the additional labor involved. When such a method is not used, published records should indicate the units used for each form counted.

In the present investigation the following units were used: Each unicellular alga, such as Synedra, Navicula, and Stephanodiscus, was counted as one, regardless of size. With algae like Pediastrum, Coelastrum, Oocystic, and Coelosphaerium, which occur in rather definite colonies, each colony was counted as a unit, regardless of size. Some difficulty was encountered in deciding on a satisfactory method of counting the filamentous forms and those which occur in colonies easily broken up in the centrifuging process. In such cases it was necessary to choose units arbitrarily. For Melosira, Oscillatoria, Lyngbya, Anabaena, and Aphanizomenon, a filament 300 microns long was counted as a unit; for Fragilaria a filament 100 microns long. Units for colonies of variable size were; Scenedesmus, 4 cells; Tabellaria, Diatoma, Crucigenia, and Asterionella, 8 cells; Dinobryon, 5 cells; and Merismopedia, 16 cells. In counting, no record was kept of the abundance of different species of the same genus; all species of a genus were counted together. The protozoa which lack plant-like characteristics were so rare in the plankton that they were disregarded in counting.

One of the disadvantages of the centrifuge method of concentratng the plankton is that certain organisms lose their normal appearance nd are difficult to identify under the low power of a microscope. With ost organisms this loss of normal appearance results merely in a slowng of the counting process, but with Aphanizomenon the result may be ore objectionable. Aphanizomenon normally occurs in bundles of filaents, but the bundles are commonly broken during the process of cenrifuging. The individual filaments have a close superficial resemlance to those of Oscillatoria, and may be counted as such. In all robability the counts of Oscillatoria in this report have been increased o some extent by the accidental inclusion of filaments of Aphanizomenon.

Acknowledgments

Dr. Albert Mann, U. S. National Museum, identified certain of he diatoms collected in 1929, and Dr. Helen Brown, The Ohio State niversity, identified many of the algae taken in 1930. Statistical nalysis of the plankton curves was done by Dr. Ralph Hile, U. S. Bureau f Fisheries. The writers are glad to acknowledge the help of these nvestigators.

Data and discussion

Qualitative data

The plankton algae other than diatoms have been treated in a ecent paper (Tiffany, 1933), and a list of them is not necessary here. n number of genera and species, the list is headed by the hlorophyceae, with 36 genera and 77 species. The Diatomeae are second ith 20 genera and 32 species; the Myxophyceae third with 12 genera and 2 species. The remaining classes have few representatives; Heterokonteae, genera and 5 species. Chrysophyceae, 3 genera and 5 species; inophyceae, 2 genera and 3 species; Euglenineae, 4 genera and 6 species. he entire list comprises 80 genera and 150 species. It is hoped that the iatoms will soon be studied in as great detail as the other groups.

Quantitative data

Island Section

Horizontal distribution

The question of the degree of uniformity in horizontal distribuion of plankton in lakes has been a controversial one since the beginning f plankton investigations. Without attempting to trace the history of the controversy, it may be said that students of the phytoplankton of inland lakes now generally assume essential uniformity where conditions of the environment are uniform. By essential uniformity is meant such uniformity that samples taken at one point will yield results fairly representative of a large area having similar conditions. In the study of small inland lakes of regular outline and bottom configuration, it is standard practice to take samples at one point in the limnetic region and allow them to represent the lake as a whole.

Data collected during the present investigation showed clearly that the phytoplankton was not uniformly distributed in the different sections of Western Lake Erie, and this is one of the principal conclusions of the report. Also there was evidence of lack of uniformity in the Island Section, and it was necessary to devise a sampling program adequate to avoid inaccuracies from that cause. This was done by taking samples from several stations rather than from one. In the interest of economy of space, the data from the Island Section are not presented here. The question of adequacy of the sampling program will be considered in a later section.

Vertical distribution

The subject of vertical distribution of phytoplankton organisms is given a subordinate position in this report because of the essential uniformity which prevails in Western Lake Erie. Some examples of unequal distribution were noted, but in general, the inequalities were not large and probably existed for short times only. Moreover, the differences in distribution were not consistent; at times the algae were more abundant at the surface, and at other times near the bottom or at intermediate depths. On the whole, it has not been possible to correlate the inequalities in distribution with factors in the environment. On some dates the different genera were distributed in such a haphazard way that it would be hopeless to attempt to explain it. Essential uniformity is to be expected from the fact that the water is usually homothermous, permitting mixture of the floating vegetation by winds. Periods of thermal stratification are of such short duration that there is little opportunity for the building up of strata of the passive plankters. That the phytoplankton is usually distributed with essential uniformity is indicated by the data in Tables 49 and 50.

Seasonal distribution

Season of 1929

Seasonal distribution of phytoplankton groups. The season of 1929 covered a period from late May to late October, inclusive. Table 51 shows the seasonal distribution of the groups of plankton algae during

s period of five and a half months. Each month was divided into
periods of roughly two weeks, and the counts from all stations
ited in each period were averaged together to determine the
ndance for that period. The second column in Table 51 gives the mean
the dates on which samples were taken, and the third column indicates
number of stations visited. Only eight stations were located in the
and Section, so that numbers in excess of that indicate that certain
tions were visited twice during the period. The stations were as
lows: 18, 37A, 59A, 82, 158, 68, 75, and 8F (Fig. 1). Originally it
planned to visit each station at intervals of approximately two
ks. For various reasons it was not possible to adhere to the plan
ctly. In late August and early September, only two stations were
ited in each period. Late June and early October also were poorly
resented.

The most important groups were diatoms (Diatomeae), greens
lorophyceae), and blue-greens (Myxophyceae). The column headed
hers" includes Heterokontaea, Chrysophyceae, Dinophyceae, and
lenineae. The results are shown graphically in Fig. 13.

The diatoms were rather abundant at all times, but showed two
tinct periods of marked production. In late May the mean number of
toms in the Island Section was 39 thousand units per liter of lake
er. They increased rapidly and reached the spring maximum of 99
usand units per liter in early June. The low point for the season
e in early July (26 thousand units); during late July and August
counts were higher and rather constant. In early September the
toms increased rapidly to 140 thousand units, and continued on to
thousand in the last half of the month. There was no further in-
ease in early October, but in late October the number rose to 261
usand units, the high for the season. Whether this was the peak
the year or whether they continued to multiply for some time must
ain a matter of conjecture. As far as the data go they indicate
periods of abundance for 1929, a minor one in early June and a
or one in September and October.

The green algae remained constant at about 6 thousand units per
er from late May through early July. In late July and August they
reased gradually to 15 thousand units, but in early September in-
ased abruptly to 71 thousand, and reached a maximum of 128 thousand
late September. Thereafter they declined and at the end of the
son they were 33 thousand units per liter. Thus the greens ex-
ited only one period of abundance, which came in autumn.

In the early part of the season the blue-green algae were
y rare, but in early August they increased rapidly to 23 thousand
ts, and continued to increase to a maximum of 197 thousand units
late September. In early October they dropped suddenly to 75 thousand
ts, and declined only slightly more in the remaining part of the month.

Table 51.- Seasonal distribution of phytoplankton groups in the Island Section, 1929. Abundance in thousands of units per liter.

Period	Mean date	No. of stations	Diatoms	Greens	Blue-greens	Others	Total
May 16-31	25	11	39	6	0.7	0.01	46
June 1-15	9	8	99	7	3	0.09	109
June 16-30	21	4	50	5	0.7	0.00	56
July 1-15	6	10	26	6	0.5	0.06	33
July 16-31	24	6	60	11	4	0.6	76
August 1-15	10	8	48	13	23	0.4	84
August 16-31	24	2	55	15	72	1	143
September 1-15	12	2	140	71	144	2	357
September 16-30	20	8	196	128	197	0.2	521
October 1-15	9	6	194	105	75	0.00	374
October 16-31	20	3	261	33	62	1	357

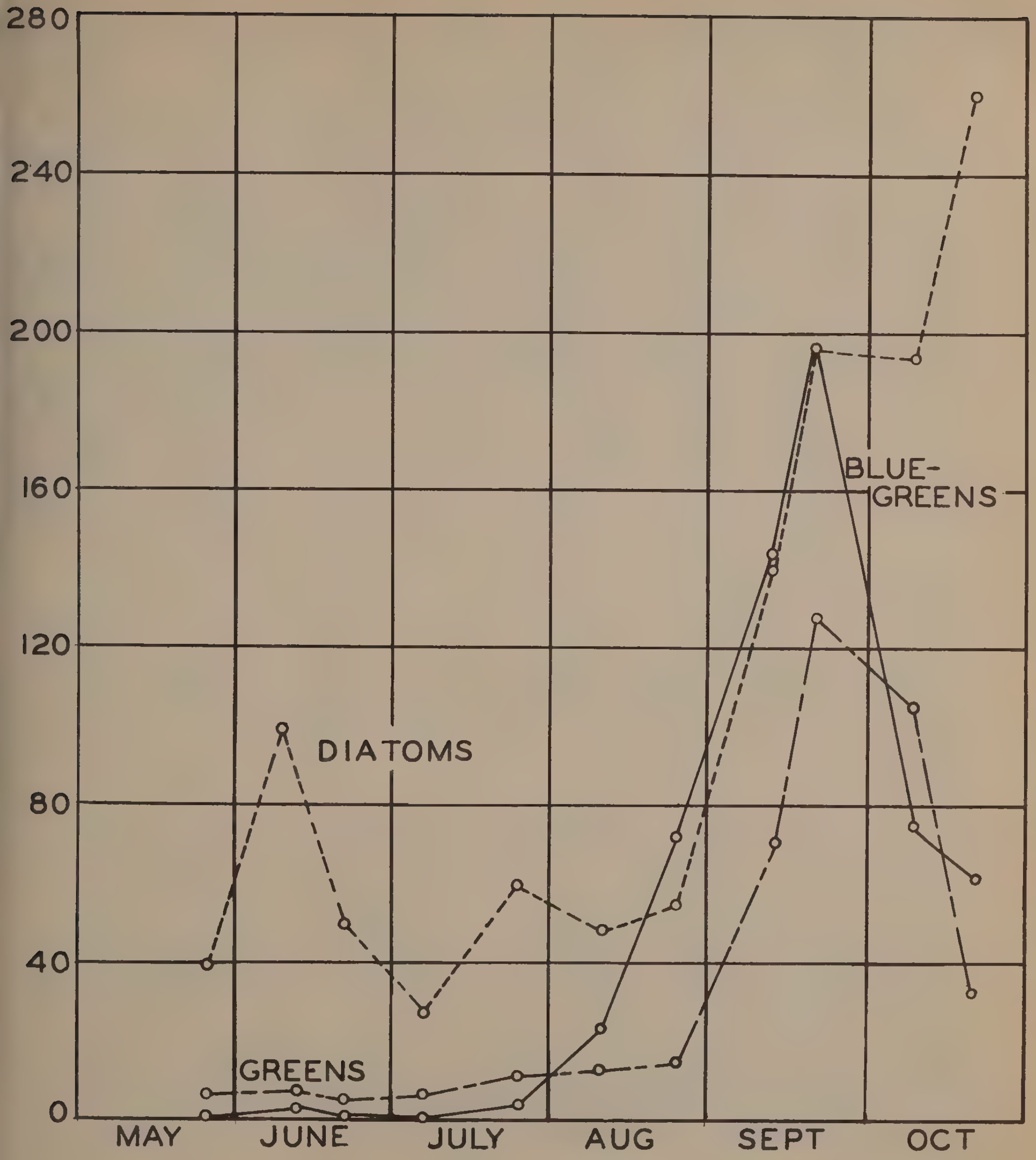

Fig. 13--Seasonal distribution of diatoms, greens, and blue-greens in the Island Section, 1929. Data taken from Table 51.

Thus the blue-greens had only one period of abundance, and this fell in the month of September.

Algae other than diatoms, greens, and blue-greens were too rare at all times to require discussion.

A glance at Fig. 13 is sufficient to show that the plankton was dominated by diatoms for most of the season. From late May to early August the plankton was almost exclusively composed of diatoms. From late May to late July, greens and blue-greens were both rare, but greens were consistently the more abundant. In August the blue-greens outnumbered the greens, and equalled the diatoms during late August and September. Greens and blue-greens each reached their maxima in late September, at which time the blue-greens were much the more abundant. In October, both greens and blue-greens declined, while the diatoms continued to increase and reached their maximum when the season closed. Except for the brief period in late summer and early autumn, the diatoms were distinctly the most abundant of the three groups.

The phytoplankton as a whole showed two periods of abundance, a minor maximum composed essentially of diatoms in spring, and a tremendous maximum in early autumn, which was contributed to by all of the three groups.

Seasonal distribution of genera. Table 52 shows the seasonal distribution of the various genera of algae which made important contributions to plankton in the season of 1929. The figures for abundance are average of counts made for all stations visited in each period of two weeks.

In addition to being the most important group numerically, the diatoms were represented by more genera of importance than the greens or blue-greens. Eight genera of diatoms appeared in considerable abundance at some time during the season. Of these, Asterionella, Fragilaria, Melosira, Synedra, and Stephanodiscus were particularly conspicuous. Tabellaria, Navicula, and Amphora were relatively rare. Asterionella had two periods of great abundance. In the spring maximum there were 29 thousand units per liter; it nearly disappeared in the summer but increased to a second maximum of 100 thousand units in late October. Fragilaria showed one period of abundance; it was rare until September, when it increased markedly, reaching a maximum of 33 thousand units in the last half of that month. Melosira, like Asterionella, showed two maxima of about the same magnitude, one in

Table 52.- Seasonal distribution of the principal phytoplankton organisms in the Island Section, 1929. Abundance in thousands of units per liter. T indicates trace. or less than one hundred units per liter.

Group	Genus	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	Aug. 1-15	Aug. 16-31	Sept. 1-15	Sept. 16-30	Oct. 1-15	Oct. 16-31
Diatoms	Asterionella	4	29	14	1	2	1	7	19	24	66	100
	Fragilaria	1	4	4	0.9	2	2	2	30	33	21	18
	Melosira	13	22	5	2	2	0.8	7	8	28	25	10
	Synedra	4	5	1	0.4	20	0.7	0.6	35	54	41	94
	Tabellaria	1	6	2	2	2	0.4	0.3	0.3	6	4	5
	Stephanodiscus	11	29	25	19	30	43	37	37	40	26	18
	Navicula	3	2	0.3	0.5	2	0.3	0.6	3	3	5	13
	Amphora	-	-	-	T	-	-	-	7	7	3	1
Greens	Oocystis	0.4	0.8	1	2	3	3.0	0.6	7	24	78	8
	Scenedesmus	4	3	2	2	3	2	5	10	17	11	9
	Dictyosphaerium	T	0.2	0.2	T	0.6	0.3	-	42	47	8	7
	Coelastrum	0.2	0.2	T	0.6	2	5	5	11	38	7	3
Blue-greens	Coelosphaerium	T	T	-	0.2	0.7	6	29	28	-	0.2	0.8
	Oscillatoria	0.6	2	0.4	0.2	1	T	-	5	21	19	26
	Merismopedia	-	T	0.2	0.1	1	15	38	84	129	28	6
	Gomphosphaeria	-	-	-	-	0.3	0.1	0.6	28	48	24	21

early June and a second in late September. Synedra was rare in spring and summer (except in late July), increased explosively in September and was most abundant in late October (94 thousand units per liter).

Tabellaria was never very abundant, but was definitely more numerous in spring and autumn than in summer. The maxima reached 6 thousand units each. Stephanodiscus was unique among the algae in being abundant at all times and in showing relatively slight changes in abundance. It was least numerous at the beginning and end of the season; during June-July the mean count was 23 thousand and in August-September the mean was 39 thousand units. Stephanodiscus was the most consistently abundant of the phytoplankton organisms. Navicula was rare in spring and summer, increased somewhat in September and reached a maximum of 13 thousand units in late October. Amphora was present only in traces prior to September, and was never more numerous than 7 thousand units per liter. Rhizosolenia, which is not listed in the table, was present only in spring and autumn and never exceeded 2 thousand units per liter. Surirella and Gyrosigma were rather consistently present but never in large numbers.

The spring maximum of diatoms was composed largely of Asterionella, Melosira, and Stephanodiscus. The autumn maximum was more varied in composition; with large numbers of Asterionella, Fragilaria, Melosira, Synedra, and Stephanodiscus. During the months of July and August, the diatoms were almost exclusively represented by Stephanodiscus, except in late July, when Synedra was also abundant.

Only four genera of green algae appeared in the plankton in large numbers during the season of 1929. They were Oocystic, Scenedesmus, Dictyosphaerium, and Coelastrum. All were rare in spring and summer, and abundant in autumn. Oocystic began to increase in early September, reached the maximum of 78 thousand units per liter in early October, and declined to 8 thousand units in late October. Scenedesmus was the most consistently abundant green alga during the spring and summer, but was less conspicuous in autumn. The peak of 17 thousand units was attained in late September. Dictyosphaerium was absent in late August and very rare prior to that time. It suddenly became abundant in early September (42 thousand units) and was about equally abundant in late September. In October it became relatively rare again. Coelastrum was rare in spring and early summer, increased somewhat in late summer, and reached a maximum of 38 thousand units in late September. Like Dictyosphaerium, Coelastrum was rare in October. Thus, each of the important green algae had only one period of abundance and this fell in September and October. Of the genera not listed, Crucigenia, Sphaerocystis, Eudorina and Pandorina were present in many of the spring and summer samples, but were lacking in autumn. Cosmarium was found in all but one of the periods, and in late October there were 4 thousand units. Pediastrum was consistently present, but always in small numbers. Kirchnerella, Errerella, Closterium, Ankistrodesmus, and Westella were very rare and were restricted to the summer months.

Four genera of blue-green algae were important constituents of the plankton: Coelosphaerium, Oscillatoria, Merismopedia, and Gomphosphaeria. All were rare prior to the middle of August. Coelosphaerium was first present in considerable numbers in early August, and was abundant in late August and early September (29 and 28 thousand units). It was not noted in late September, and was rare in October. Oscillatoria was present in every period except late August, but was abundant only in the last three periods, showing a maximum of 26 thousand units in late October. Merismopedia was the most conspicuous of the blue-greens. It first became abundant in early August and increased gradually to a maximum of 129 thousand units in late September. Gomphosphaeria was absent until mid-summer and rare during the remainder of the summer. It increased rapidly in early September and reached a maximum of 48 thousand units in late September. In October it was about one half as abundant as at the peak. Microcystis was present in only six periods, and the maximum count was 4 thousand. Anabaena was noted in only four periods, and was always rare. Aphanizomenon was found in five periods, with a maximum count of 5 thousand at the end of the season. Lyngbya was present only in October and then in small numbers.

Genera belonging to groups other than the diatoms, greens, or blue-greens, such as Dinobryon, Ceratium, Peridinium, and Euglena were noted from time to time but were never conspicuous in the plankton.

It should be noted that the foregoing account refers only to the open waters of the lake and not to the shallow, protected areas along shore and about the islands. Such genera as Volvox, Eudorina, Gonium, Anabaena, Microcystis, Aphanizomenon, Euglena, and Ceratium may each be explosively abundant for a few days in the protected areas, and thereafter occur only sparingly or not at all. Apparently these "blooms" are localized and have little effect on the plankton of the open waters.

Season of 1930

Seasonal distribution of phytoplankton groups. The sampling season of 1930 was begun in early April and discontinued in early October. Seasonal changes in abundance for this period are shown in

Table 53 and in Fig. 14. The number of stations was reduced from eight in 1929 to six in 1930; Stations 82, 68, and 75 were abandoned, and Station 72 was substituted for Stations 68 and 75 (Fig. 1). The month of April is poorly represented by stations because the regular program was not begun until May, but none of the succeeding periods is represented by less than four stations.

The diatoms were rather abundant in April, and increased rapidly in May, reaching a spring maximum of 180 thousand units per liter in the last half of the month. During June there was a marked decline, and the low point of the season was reached in early July. The counts remained low in late July and early August. In late August the diatoms began to increase toward the autumn maximum, which came in late September. The maximum count of 242 thousand units is probably higher than it should be, because of a local aggregation of Stephanodiscus at one station. In early October there was a second major decline to 124 thousand units per liter. Thus, the diatoms exhibited two periods of abundance, the first in spring (late May), and the second in autumn (late September).

The green algae were present only in traces in April. They increased somewhat in May, but declined in June almost to the vanishing point. In July there was a marked increase to 39 thousand units per liter. The increase during August was slight, but in September they again increased rapidly, reaching the maximum of 99 thousand units in late September. Following this there was a sharp decline to 60 thousand in the first few days of October. Disregarding the small increase of greens in May, this group had one period of abundance, which began in July and reached its culmination in September.

The blue-green algae were very rare at the beginning of the season, increased slightly in May, and became rare again in late June. In July and August, they increased rapidly, reaching a count of 71 thousand units in late August. The count remained at this level in early September, but rose sharply to the season's maximum of 203 thousand units in the latter part of that month. As the season closed the count was still high, having declined very little from the maximum. Thus, the blue-green had only one period of great abundance, and this came in autumn.

The plankton was dominated by diatoms during the first three months of the season. In July, all three groups were about equally abundant, and in August, diatoms were outnumbered by both greens and

Table 53.- Seasonal distribution of phytoplankton groups in the Island Section, 1930. Abundance in thousands of units per liter.

Period	Mean date	No. of stations	Diatoms	Greens	Blue-greens	Others	Total
April 1-15	4	2	68	0.5	0.5	0.00	69
April 16-30	20	2	73	3	3	1	80
May 1-15	9	6	145	14	13	2	174
May 16-31	21	5	180	14	10	0.6	205
June 1-15	7	5	102	9	6	0.8	118
June 15-30	24	5	52	3	3	0.8	59
July 1-15	8	5	14	19	9	0.04	42
July 16-31	23	4	36	39	29	0.5	104
August 1-15	5	6	15	43	51	0.8	110
August 16-31	22	6	39	45	71	0.2	155
September 1-15	5	5	77	54	69	0.00	200
September 16-30	19	6	242	99	203	0.2	544
October 1-15	2	6	124	60	176	0.00	360

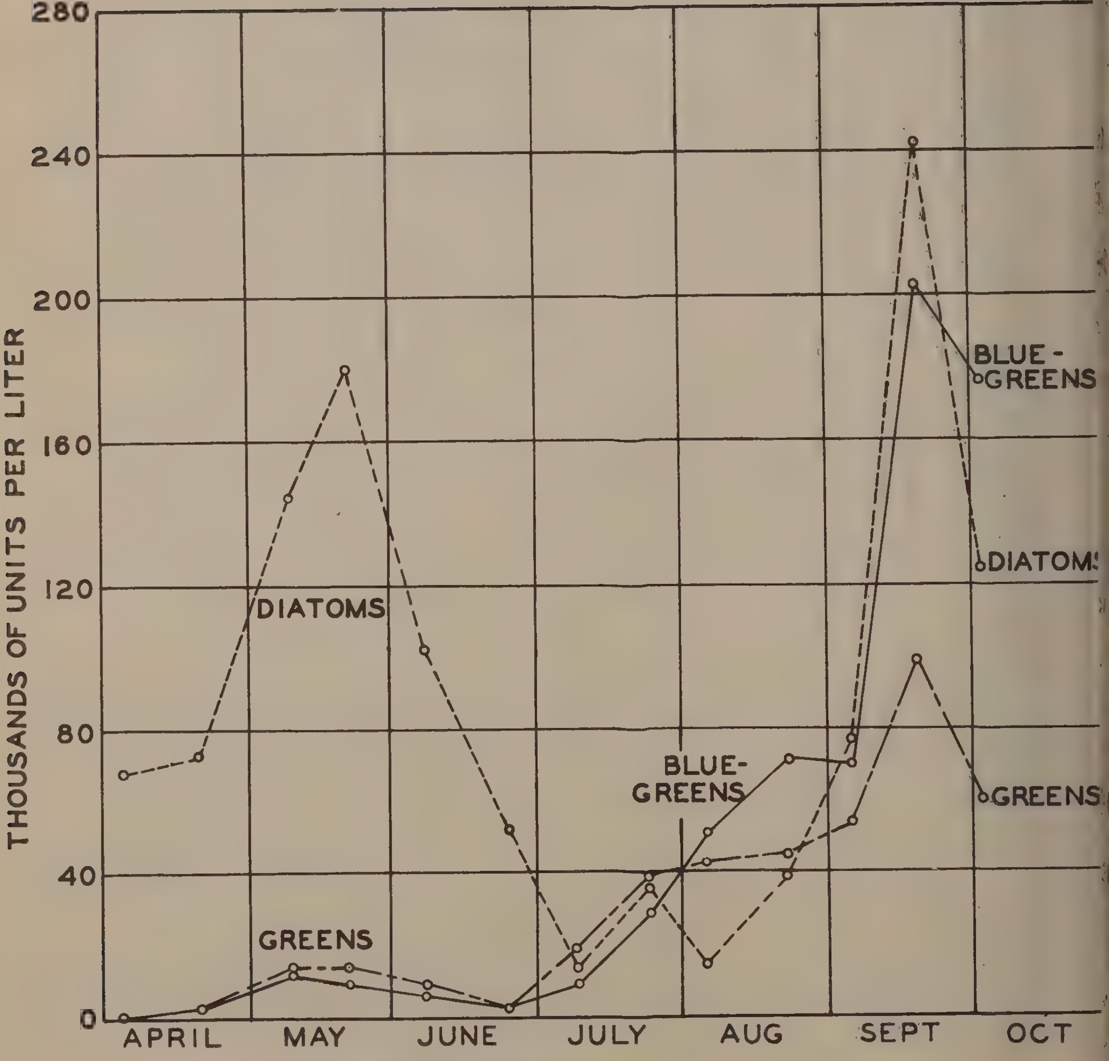

Fig. 14--Seasonal distribution of diatoms, greens, and blue-greens in the Island Section, 1930. Data taken from Table 15.

blue-greens. The diatoms recovered in September and were again more abundant than greens or blue-greens. In early October, diatoms were less abundant than blue-greens, but more abundant than greens. In spring and early summer, greens were slightly more abundant than blue-greens, but this relation was lost after July, when blue-greens greatly outnumbered greens.

The phytoplankton as a whole showed two periods of great abundance. The first came in May, and was made up almost exclusively of diatoms. The second came in September, and was composed of all three groups, but diatoms and blue-greens were especially abundant.

Seasonal distribution of genera. Table 54 shows the seasonal distribution of the most important genera encountered in the plankton during the season of 1930. As in Table 52, the figures for abundance are averages based on counts from all stations visited in each period of two weeks.

Of the eight genera of diatoms listed, only Asterionella, Melosira, and Stephanodiscus showed two pronounced maxima. The remaining five showed the usual spring maximum, but in autumn they were only slightly more abundant than during the summer period of decline. All genera except Stephanodiscus were more abundant in spring than in autumn. Asterionella reached its high count of 23 thousand units per liter in early June. It declined in summer, but recovered to 16 thousand units in early October. Fragilaria was less abundant than Asterionella, and reached its maximum several weeks earlier. For some unknown reason it became abundant in late July (12 thousand units), at which time it was the dominant diatom. Melosira was most numerous in late May (31 thousand units); in late September and early October the count was about one half as great. Synedra was a conspicuous form in April and early May, almost disappeared in summer, and increased only slightly in autumn. Tabellaria reached a maximum of 31 thousand units in early June. The counts of late September and early October were lower than some of the mid-summer counts, but higher than the minimum of early September. The spring maximum of Stephanodiscus came in early April and the minimum in late June. During the summer it gradually increased and reached the season's maximum of 208 thousand units in late September. This figure is probably too high as an average, due to the tremendous count at Station 59A on September 18. However, there is little doubt that Stephanodiscus was the dominant diatom during September and early October. Navicula was rare at all times, but reached its highest counts in May. Rhizosolenia was the most abundant diatom during the spring, with a maximum of 100 thousand units in late May. It was absent or rare

Table 54.- Seasonal distribution of the principal phytoplankton organisms in the Island Section, 1930. Abundance in thousands of units per liter.

Group	Genus	April 1-15	April 16-30	May 1-15	May 16-31	June 1-15	June 16-30	July 1-15	July 16-31	Aug. 1-15	Aug. 16-31	Sept. 1-15	Sept. 16-30	Oct. 1-15
Diatoms	Asterionella	12	11	17	15	23	12	1	2	1	1	0.8	8	16
	Fragilaria	2	12	7	4	5	6	0.7	12	0.1	0.5	0.4	4	7
	Melosira	8	7	19	31	16	2	1	3	1	2	3	16	16
	Synedra	16	18	17	12	5	2	2	5	0.3	0.3	0.7	4	2
	Tabellaria	3	14	18	9	31	27	2	4	7	1	0.3	1	2
	Stephanodiscus	22	6	5	3	6	1	4	8	11	34	71	208	79
	Navicula	0.3	0.5	2	2	0.4	0.2	0.4	-	-	0.3	0.4	0.2	-
	Rhizosolenia	0.2	2	52	100	22	-	0.2	0.2	-	-	-	-	3
Greens	Oocystis	-	0.5	-	-	0.8	-	2	3	3	3	0.6	2	2
	Scenedesmus	-	0.5	8	9	2	2	3	1	0.8	2	1	4	4
	Dictyosphaerium	0.5	-	-	-	0.2	-	0.6	3	2	6	9	22	13
	Coelastrum	-	-	0.2	0.5	0.2	-	0.2	4	21	9	13	18	4
	Sphaerocystis	-	-	0.7	2	2	0.2	3	0.2	0.7	8	8	2	-
	Pediastrum	-	0.2	0.2	0.1	0.6	0.2	3	0.6	0.2	2	2	6	-
	Tetrastrum	-	-	-	-	-	-	0.4	-	0.7	3	3	4	4
	Ankistrodesmus	-	-	-	-	0.2	0.4	2	17	1	2	7	13	13
	Westella	-	-	-	1	0.2	-	2	8	10	8	7	22	16
Blue-greens	Coelosphaerium	0.5	-	3	4	1	0.8	3	10	13	10	6	12	13
	Oscillatoria	-	3	10	4	3	0.4	3	6	14	12	6	45	28
	Merismopedia	-	-	0.3	-	-	0.2	0.6	4	17	29	31	30	34
	Gomphosphaeria	-	-	-	-	-	-	0.4	-	0.4	-	0.4	0.7	3
	Microcystis	-	-	-	0.8	2	1	1	8	6	19	24	113	95

during the warm months and reappeared in small numbers in early October. Amphora was not observed in 1930.

In spring, a number of diatoms were abundant and some of them were abundant for a long time. At the maximum for the group (late May), Rhizosolenia was dominant. The next most numerous form at that time (Melosira) had a count less than one third as great. In autumn, Stephanodiscus was far more abundant than any other form, and it determined the time of maximum abundance for the group. The only other genera which made important contributions were Asterionella and Melosira. Stephanodiscus was the most consistently abundant form in summer also.

None of the green algae was extremely abundant in the season of 1930, but the group made a creditable showing owing to the large number of genera which made important contributions to the plankton. Nine genera were present in considerable numbers at some time during the season. Oocystis was rare or wanting in the early part of the season; in July and after it was present in small but fairly constant numbers. Scenedesmus was present in every period but one, but was most abundant in May (8 and 9 thousand units). This form was largely responsible for the slight upward bend in May in the curve shown in Fig. 14. Dictyosphaerium was most abundant near the end of the season, with a maximum of 22 thousand units in late September. Coelastrum was one of the more abundant greens. Rare or absent in the first half of the season, it reached a high count of 21 thousand in early August. The count in late August was lower, but it increased again in September. At the end of the season Coelastrum was on the decline. Sphaerocystis was present from early May to late September, and was most abundant (8 thousand units) in late August and early September.

Pediastrum was encountered in all periods except the first and last, but was usually very rare. The high count of 6 thousand units was recorded for late September. Tetrastrum first appeared in July and never exceeded 4 thousand units. Ankistrodesmus was absent prior to June. In the last half of the season it showed two distinct periods of abundance; one in late July (17 thousand units) and another in the last two periods (13 thousand units). Westella appeared in late May, was rather abundant in late summer, and reached the peak of 22 thousand units in late September. It should be noted that Scenedesmus was the only green alga to reach its maximum in the first half of the season. All of the others showed their greatest abundance after the middle of July. The greens not listed in the table were unimportant constituents of the plankton. Cosmarium appeared frequently but in small numbers. Closterium was absent from most of the samples, but in late September had an average count of 3 thousand units. The remaining forms were too rare to require mention.

The blue-green algae were represented by only a few important genera. Coelosphaerium was more abundant in May than in April or June, but was rather consistently abundant after the middle of July, with an average of 11 thousand units per liter. Oscillatoria also was abundant in May. These two genera were responsible for the minor peak in the curve for blue-greens in May (Fig. 14). Following a decline in June, Oscillatoria again increased and reached a maximum of 45 thousand units in late September. Merismopedia was rare or wanting in the early half of the season, but increased rapidly in early August, and maintained a level near 31 thousand units for the last four periods of the season. Gomphosphaeria was very rare in 1930, only once exceeding 1 thousand units per liter. Microcystis appeared in small numbers in late May and remained rare until late July. In late August it increased greatly and reached the season's maximum of 113 thousand units in late September. During the last two periods it was the most abundant blue-green in the plankton. Thus, Coelosphaerium and Oscillatoria were the only genera to appear in considerable numbers in spring, and all genera were more abundant in late summer and early autumn than earlier in the season.

The genera belonging to groups other than diatoms, greens, or blue-greens, appeared from time to time, but always in small numbers.

Comparison of the seasons of 1929 and 1930

It is evident from the foregoing discussions of seasonal distribution that the distribution in the two years was not exactly the same. The differences are particularly striking for the genera, and less so for the groups of phytoplankton organisms. It appears that differences in the genera tended to compensate for each other, so that the curves for groups were not as far different as one might expect. In the following section, differences and similarities in seasonal distribution both of groups and genera will be considered.

Diatoms. In order to facilitate comparison of the distribution of diatoms in the two years, Fig. 15 was constructed. The curves are the same as those for diatoms shown in Figs. 13 and 14, and are derived from the data in Tables 51 and 53. Comparison of the curves for diatoms is somewhat unsatisfactory. The periods of time covered were not exactly the same; the season of 1929 began later and ended later than the season of 1930. The curves agree very closely for the months of June, July, August, and September, but not for the extreme ends of the seasons. In the section on adequacy of the sampling program (p. 172) the curves are compared mathematically for comparable periods of time. In the following discussion, emphasis will be placed on differences between the curves, rather than on their similarities.

Turning our attention to spring, it is obvious that the curves disagree with respect to actual abundance and the times of maximum abundance. The count at the time of greatest abundance in 1930 was nearly twice as great as the corresponding count in 1929. The difference was due in large part to the great abundance of Rhizosolenia in 1930. This form made up more than half of the total count of diatoms in late May, whereas in 1929 it was extremely rare. In spite of the great abundance of Rhizosolenia in 1930, it was not alone responsible for the early appearance of the maximum of the diatoms. This statement may be verified by inspection of Table 54. Even if Rhizosolenia were disregarded, the diatoms would have reached their maximum in late May rather than in early June, as in 1929; but the count would have been almost the same as in early June, 1929. This shifting of the time of greatest abundance possibly was due to the higher water temperatures in 1930 as compared to 1929 (Figs. 8 and 9). It is generally recognized that the maximal production of diatoms occurs at times of rather low temperatures (Steuer, 1910, p. 538), hence we should expect that the spring maximum of diatoms would come earlier in a warm season than in a cool one. However, Pearsall (1923) and others have expressed the opinion that temperature in itself is of little importance in determining periodicity of diatoms.

The investigation was not carried on for a sufficient length of time in autumn to cover all of the autumnal period of abundance and subsequent decline. In 1929, sampling was continued into late October, but at that time the diatoms as a group showed no indication of declining numbers. In 1930, no samples were taken after the first few days of October. From the curve in Fig. 15 it might be concluded that the diatoms had reached their maximum in late September and were declining. But the high point in the curve was almost entirely due to Stephanodiscus, and there is some question regarding the accuracy of that point. There appeared to be a local aggregation of Stephanodiscus at Station 59A on September 18, and the true mean number of diatoms for the Island Section was probably lower than the figure obtained (242 thousand units). Furthermore, reference to Table 54 shows that the diatoms other than Stephanodiscus had rather low counts when the season closed. In view of the fact that water temperatures in early autumn, 1930 (Figs. 8 and 9), were in excess of those for the same time in 1929, it seems probable that the autumn maximum of diatoms came later in 1930 than in 1929, and is not included in the records at hand.

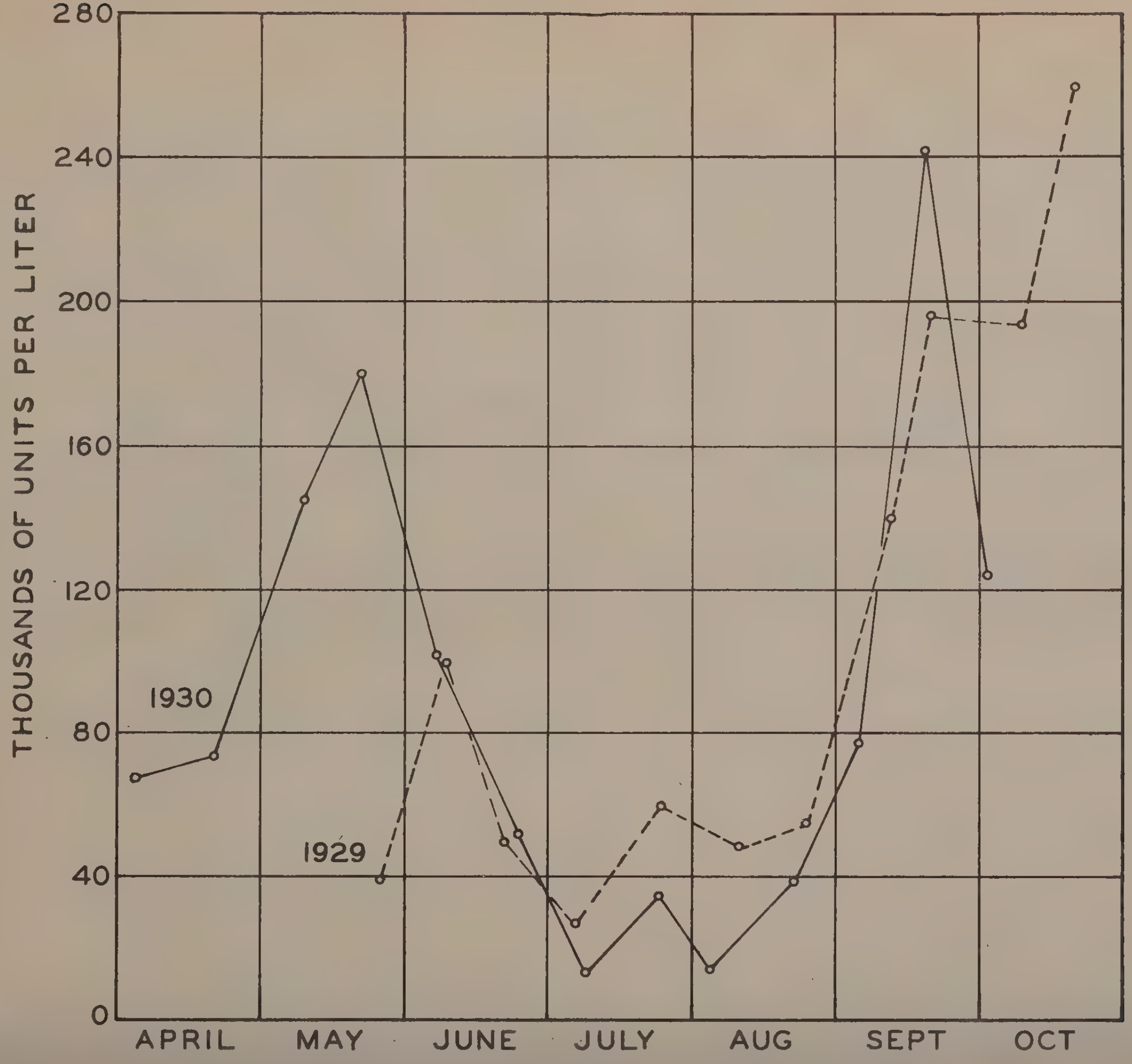

Fig. 15--Comparison of seasonal distribution of diatoms in 1929 and 1930. Data taken from Tables 51 and 53.

According to this view, the apparent maximum of diatoms in late September was a minor peak due to the earlier appearance of the maximum of one form: Stephanodiscus.

A natural corollary of this conclusion regarding the abundance of diatoms after the close of the season in 1930 is that the autumn maximum was greater than that of spring. Because of the probable inaccuracy of the figure for average abundance in late September, it is unsafe to reach that conclusion on the basis of the data as they stand. However, the circumstantial evidence cited in the preceding paragraph, and the undoubted superiority in numbers in autumn over spring of 1929, point toward the conclusion.

Although diatoms may be regularly more abundant in autumn than in spring in Western Lake Erie, the condition is not common to all shallow lakes. As early as 1894, Whipple reported on the seasonal distribution of diatoms in lakes and reservoirs of Massachusetts. Comparing deep and shallow lakes, he found that the deep lakes showed two distinct periods of abundance, one in spring and another in late autumn or winter, while the shallow lakes showed little or no production in autumn. Certainly this is not the case in Western Lake Erie. Whether or not the autumn maximum regularly exceeds the spring maximum, the data for 1929 and 1930 show two periods of abundance very definitely.

Whipple believed that the two periods of abundance of diatoms in the deeper lakes were associated with the two periods of circulation of the water; that nutritive materials for the plants became isolated in the stagnant lower water, and when they became available again, diatom production was increased. While this interpretation fits in well with his data, it can not explain autumnal increases in shallow lakes where there is no stagnation in summer. Tressler and Domogalla (1931) called attention to this fact in connection with their study of Lake Wingra, Wisconsin. In this shallow lake (Maximum depth, 4.25 meters), the diatoms had a definite bimodal distribution, although the abundance in spring was greater than in autumn. Marsh (1903, p. 14) believed that Whipple's theory explained the seasonal distribution of diatoms (particularly Cyclotella) in Lake Winnebago, but this could not be the case, because the lake lacks thermal stratification in summer (Marsh, page 6).

A supplementary theory of diatom periodicity concerns the effect of flood and drought on the concentration of nutritive salts. Pearsall (1923 and 1932) is the principal advocate of this theory, although earlier workers (some of whom were not quoted by Pearsall) laid the foundation for it. Transeau (1916) reported that, contrary to the accepted view, the salts are most concentrated in surface waters (of Illinois) in spring and autumn, when the levels are highest, and that this is also the time of most abundant fruiting of algae. Hodgetts (1921-1922) found a varying relationship between water level and the amount of dissolved matter in a small pond. In general, the concentration was greater with low level than with high level. He believed that concentration was important in the periodicity of certain algae. Pearsall (1923) cited some examples of diatom maxima coinciding with high water and high concentration of salts. The spring maxima in Western Lake Erie came at or near the times of highest lake level. In 1929, the highest water was recorded for May, June, and in 1930, for April. However, the autumn maxima of algae came at times of low lake level in both years. Thus, the observed relation between lake level and diatom maxima in Western Lake Erie cannot be said to support Pearsall's theory of periodicity, but, on the other hand, the two seasons of observations hardly constitute an adequate test. In both years the rainfall after July was abnormal: a deficiency in August being followed by an excess in September or October (Table 5). It is possible that the excess rainfall in early autumn brought in enough nutrient material to support an unusual production of diatoms.

It does not seem worth while to call attention to all of the differences in distribution of the genera. Aside from the great abundance of Rhizosolenia, and the absence of Amphora in 1930, the principal differences are such as might be explained by the difference in the periods of time covered in the two years.

Greens. Comparison of the seasonal distribution of the green algae in 1929 and 1930 will be facilitated by reference to Fig. 16. As shown later, the curves agree very closely with respect to actual abundance, and time and degree of changes in abundance for comparable periods.

The principal differences are in the earlier appearance of large numbers and the earlier decline from the autumn maximum in 1930 as compared with 1929. Earlier appearance of large numbers in 1930 probably resulted from the higher water temperatures of that year, but the reason for the earlier decline in autumn is not obvious. The data suggest that the greens ordinarily persist a certain length of time, and that earlier increase is balanced by earlier decline.

The green algae reach their maximum abundance in summer in most of the lakes which have been studied (Steuer, 1910, p. 542). Some writers have reported spring and fall maxima, for example, Tressler and Domogalla (1931) in Lake Wingra. G. M. Smith (1924, page 110) stated that large growths usually appear only in late spring or early summer. In Western Lake Erie, greens were slightly more abundant in May than in April or June, 1930, but they were not conspicuous in the plankton before July. West and West (1912) found that the greens were most abundant in autumn in lakes of England and Scotland, and the same is true for Western Lake Erie. In both years they reached a maximum in late September, that is, at a time of declining water temperatures. The reason

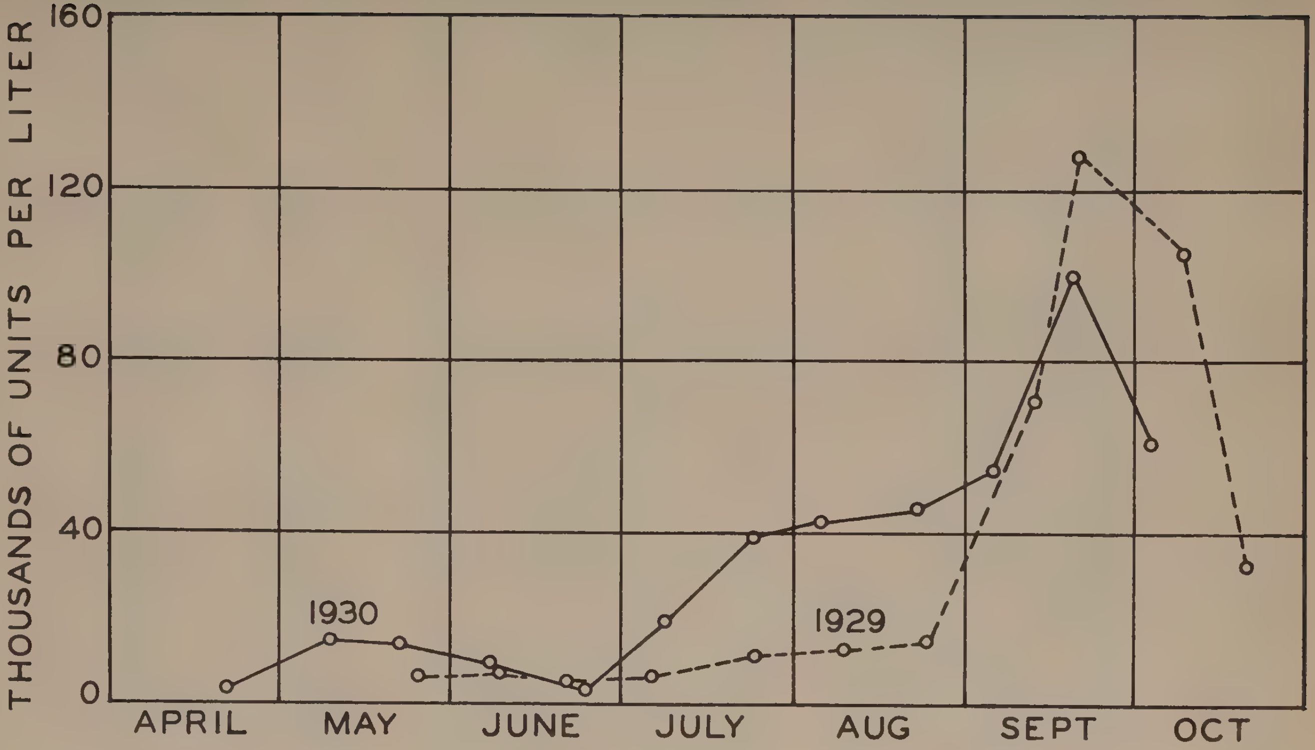

Fig. 16--Comparison of seasonal distribution of greens in 1929 and 1930. Data taken from Tables 51 and 53.

for late culmination of the greens in this lake is not evident. Whipple (1927, p. 232) stated that late growths of green algae are usually associated with stagnation, but, obviously, this explanation cannot apply to Western Lake Erie.

Taken as a group, the greens were distributed similarly in the two years, but there were some marked differences in the composiion of the group. In 1929, only four genera (Oocystis, Scenedesmus, Dictyosphaerium, and Coelastrum) were prominent in the plankton. Of these only Coelastrum and Dictyosphaerium were abundant in 1930, while Oocystis and Scenedesmus were comparatively rare. Rarity of these forms was compensated for by the addition of five genera which were rare or wanting in 1929. None of these five was extremely abundant, but combined with the four genera mentioned above, they were able to maintain the same average abundance as in 1929 during comparable periods of time. The four leading genera in 1930 were Coelastrum, Dictyosphaerium, Ankistrodesmus, and Westella.

One notable point concerning the composition of the phytoplankton is the rarity of desmids, both in species and in abundance of those present. West and West (1912) called attention to the fact that the most important factor in the distribution and abundance of plankton algae is the amount of dissolved salts in the water. They found that desmids predominate in regions having Precambrian and early Paleozoic rocks, which have small amounts of dissolved salts, particularly calcium, in the surface waters. Such waters are poor in diatoms and blue-greens, while these two groups are conspicuous in waters with a high content of dissolved salts. G. M. Smith (1924, p. 113) discussed this question at length and stated that his findings in North American lakes supported the theory of West and West. Pearsall (1922) stated the theory more precisely: desmids dominate in waters with a high basic ratio, that is, waters in which the ratio $\frac{K + Na}{Ca + Mg}$ is more than 1.5. Such waters are poor in nitrates, carbonates, and silica. Waters with a basic ratio of less than 1.5 are rich in nitrates, carbonates, and silica, and have diatoms dominant. They also support numbers of blue-greens, and greens other than desmids.

The known facts concerning the phytoplankton of the Great Lakes are in accord with this theory. In Lake Erie the ratio $\frac{K + Na}{Ca + Mg}$ is 0.17 and the mean for the five Great Lakes is 0.16 (see Table 13). Along with this low basic ratio, we find that the phytoplankton is dominated by diatoms, and that desmids play a minor part (see especially Eddy, 1927; Gottschall, 1930; and Burkholder, 1929a).

Blue-greens. The seasonal distribution of the blue-green algae in 1929 and 1930 is shown graphically in Fig. 17. On page 172 the curves are compared mathematically. They agree very closely for comparable periods of time, even more closely than the diatoms or greens.

The only marked difference between the two years was in the earlier appearance of large numbers in 1930. This point was noted for the greens also, and probably the same explanation applies in both cases, namely, the higher water temperatures in 1930. Another feature in common with the greens is the greater abundance of blue-greens in May as compared with April and June of 1930. There is no indication of this in the curve for 1929. Earlier sampling in 1929 might have detected the phenomenon, but that it was present seems doubtful from the fact that the water temperatures in May, 1929, were lower than in May, 1930, and we should expect the increase to come later rather than earlier. On the whole it appears probable that there was no vernal increase of blue-greens or greens in 1929.

In the majority of lakes, blue-greens reach their peak in late summer or in early autumn, as in Western Lake Erie, while greens culminate somewhat earlier. Temperature is generally regarded as the most important factor in determining the time of greatest abundance of both of these groups. Apparently, then, the greens prefer a slightly higher temperature than the blue-greens (but see G. M. Smith, 1924, p. 110). The data from Western Lake Erie give no evidence of this preference, for in both years the blue-greens agreed very closely with the greens with respect to the time of greatest abundance. This remarkably close agreement indicates that the two groups react in the same way to the controlling factor or factors in the environment in this lake. The reason for this agreement in Western Lake Erie, in contrast to the usual situation, is not known.

The composition of the group was somewhat similar in the two years. In 1929, Coelospherium, Oscillatoria, Merismopedia, and Gomphosphaeria made important contributions to the plankton, Merismopedia being the most conspicuous form. In 1930, Gomphosphaeria was very rare, but the other three genera were abundant again. The principal difference in the distribution of these three was that in 1930 they maintained their abundance for a longer time than in 1929. The rarity of Gomphosphaeria in 1930 was compensated for by the great abundance of Microcystis. The latter was the most abundant blue-green during late September and early October.

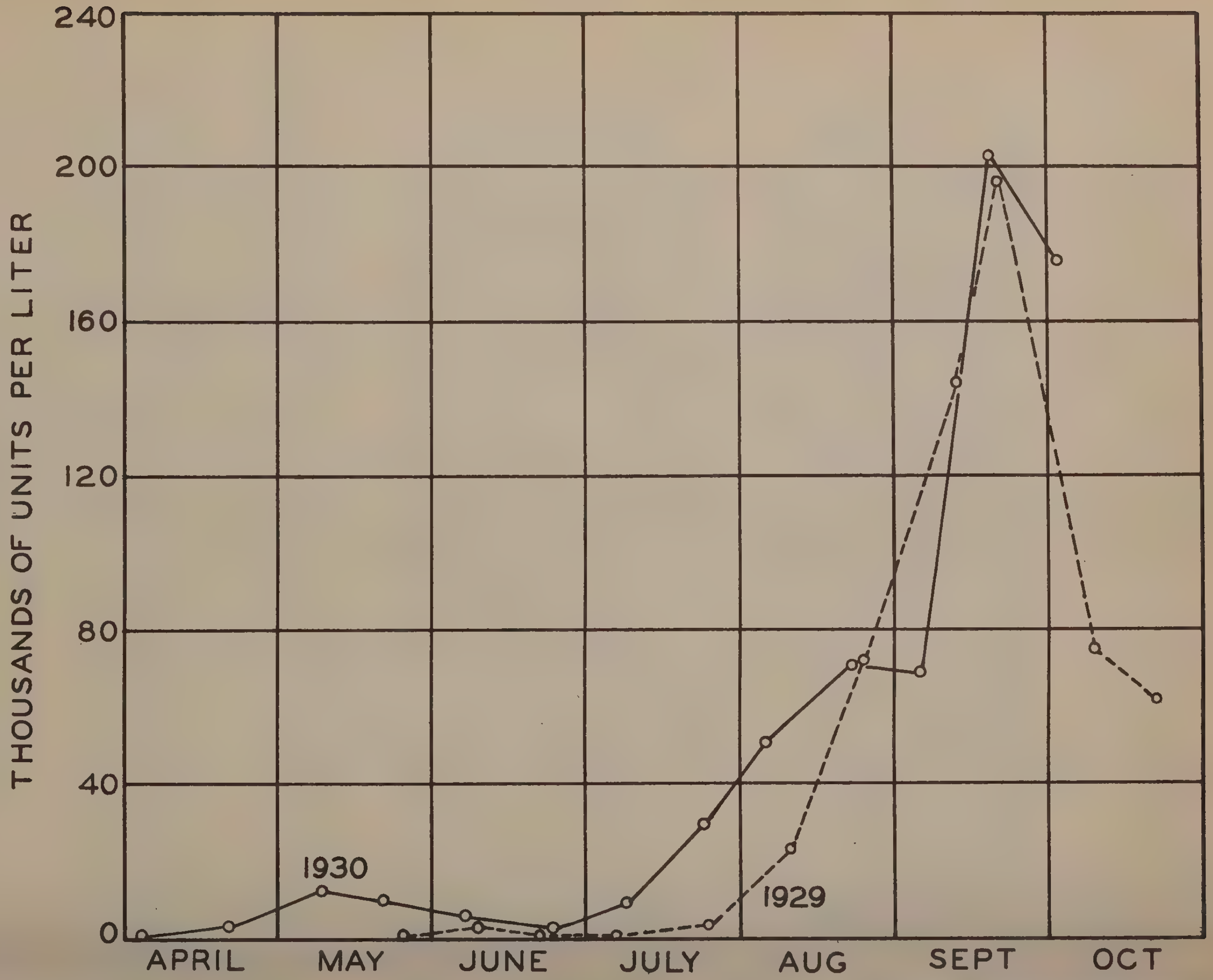

Fig. 17--Comparison of seasonal distribution of blue-greens in 1929 and 1930.
Data taken from tables 51 and [illegible]

Others. Groups other than diatoms, greens, and blue-greens were rare in both years; so rare that the counting methods employed could not determine their abundance with accuracy. Hence, it is not worth while to attempt to trace seasonal changes in abundance. These groups made negligible contributions to the bulk of the plankton.

Adequacy of the sampling program

In the section on horizontal distribution, it was pointed out that the plankton is not uniformly distributed. It may be well to consider, now, whether the sampling program as indicated in Tables 51 and 53 was adequate to show seasonal changes in abundance with an acceptable degree of accuracy.

A study of the available data from individual stations shows that the program was adequate to bring out the seasonal trends in abundance. That is, the records of individual stations agree closely as to the times of abundance and rarity of plankton. Each station showed spring and autumn maxima, and a summer minimum of diatoms. Also, each station showed maxima of greens and blue-greens in autumn only.

However, the records show some marked discrepancies in the actual abundance of organisms at different stations in the same period of time. In some cases the discrepancies are so large that caution must be used in drawing conclusions from the averages. Certainly a small difference between the averages of the same group of algae in two periods, or between two groups of algae in the same period should not be regarded as indicative of real difference in abundance. For example, it would be improper to conclude that the autumnal maximum of blue-greens was greater in 1930 than in 1929 (Fig. 17), or that greens were more abundant than diatoms in July, 1930 (Fig. 14). However, if small differences appear consistently over a period of time, it appears proper to consider them as significant. For example, prior to August in both years, blue-greens were never more abundant than greens and were equal to them in only three periods. (Figs. 13 and 14). Although the superiority in numbers of greens over blue-greens before August was never great, it was too consistent to be regarded as accidental.

In spite of the rather large differences in counts between stations during the same period of time, there are good reasons for believing that the averages give a fairly accurate record of the seasonal changes in abundance. The first reason for believing so is that the figures for average abundance during comparable periods of time in the two years are of the same order of magnitude. For the period late May - early October, which is common to both years, the average count of diatoms was 91 thousand units in 1929, and 88 thousand units in 1930 (Tables 51 and 53). For the same period, the average count of greens was 37 thousand in 1929, and 38 thousand in 1930. Corresponding figures for the blue-greens were 52 thousand and 63 thousand units. It is recognized that absolute agreement in the averages given above would not prove the reliability of the averages given in Tables 51 and 53. On the other hand, the fact that they are not widely discrepant is suggestive of reliability. That is, we should expect to find differences in abundance in the same lake in successive years, yet we should expect that these differences in abundance in the two years would not be great.

The second reason is that the curves for the two years (Fig. 15, 16, and 17) are in close agreement with respect to (1) the times of changes in abundance, and (2) the degree and direction of change. This relationship can be brought out best by determining the coefficient of correlation and its probable error for each pair of curves by means of the well-known Pearsonian formulae. Data for comparison of the curves were obtained as follows. Points on the curves for 1929 (late May to late September) were taken as X, and corresponding values for 1930, Y, were obtained by running a line vertically to the curves for 1930. These corresponding values were then applied in the following formulae:

$$r = \frac{E\,xy}{\sqrt{Ex^2Ey^2}} \quad \text{and}$$

$$P.E._r = \pm \frac{0.6745\ (1 - r^2)}{\sqrt{n}}$$

The values of the coefficients of correlation (r) for the three groups of phytoplankton organisms shown in Figs. 15, 16, and 17, are as follows:

Diatoms,	.80 ± .082
Greens,	.90 ± .042
Blue-greens,	.99 ± .005

These figures indicate a high degree of correlation between the curves for the two successive years. Agreement is especially close for the blue-greens and greens, and less so for the diatoms. Perfect correlation is not to be expected, even if the sampling program were perfectly adequate, because of differences in weather conditions in the two years, and because of the diversity of material from which the data were derived.

In view of the close agreement between the two years with regard to (1) average abundance of phytoplankton groups, (2) times of changes in abundance, and (3) degree and direction of change, it seems safe to conclude that the sampling program was adequate for the needs of the investigation. In all probability, none of the conclusions reached in this report would have been changed materially by a more complete coverage of the area studied.

Abundance of phytoplankton compared with that of other lakes

The question of the abundance of phytoplankton in the Island Section of Western Lake Erie as compared with other lakes is one of considerable interest, but the obstacles to direct comparison are great, owing to the diversity of methods and manner of reporting data employed by different investigators. Any answer given to the question at this time must be rather unsatisfactory, but it seems worthwhile to draw a few comparisons. These comparisons will be made on the basis of the amount of plankton per unit of volume of water, rather than the amount per unit of surface. In general, deep and shallow lakes of the same surface area, and situated in similar regions, produce about the same total amount of plankton; in the shallow lakes it is more concentrated than in the deep ones. From the standpoint of availability to plankton-feeding fishes, it is more important to know the concentration of the organisms than the total number present in the lake.

Before taking up a comparison of the Island Section of Western Lake Erie with other lakes, it may be well to compare abundance in this part of the lake with the part to the east. Burkholder (1929a) reported counts at several stations east of Point Pelee in parts of July, August, and September, 1928. The data indicate extreme rarity of phytoplankton as compared with Western Lake Erie. Diatoms were much more abundant than greens or blue-greens, but even in September, when diatoms were most abundant, no station had a count as high as 5 thousand units per liter.

In 1929, the area was extended to cover all of the lake east of Western Lake Erie, and samples were taken in June, July, August, and September (Burkholder, unpublished manuscript). Diatoms were most abundant in June and September. In June the highest count was made on the south shore near Fairport (about 46 thousand units per liter). Most of the stations had much lower counts, and the average (not given) would be much less than the average for Western Lake Erie in the same month. In July the diatoms almost disappeared in the central basin, but east of Long Point several stations had counts of 10 thousand or more. In August the diatoms were rare everywhere, but in September the abundance increased markedly in the central basin. The highest count was recorded for a station near Cleveland (about 230 thousand). The average for the three stations nearest Western Lake Erie was about 55 thousand, which was above the average for the whole area, and well below the average for Western Lake Erie in September (Figure 13). Asterionella, Fragilaria, Melosira, and Tabellaria were the dominant genera.

It should be mentioned here that Burkholder's results disagree with those obtained by Gottschall (1930) with regard to the abundance of diatoms near the port of Erie. Gottschall took collections from the intake pipe of the Erie water supply. The outer end of the intake pipe is not far from one of Burkholder's stations, and one would expect counts from the two sources to be somewhat alike. For August and September, 1929, Gottschall reported counts ranging from about 20 thousand to about 600 thousand units per liter, while the counts from Burkholder's station nearby did not exceed 2 thousand. It would be of considerable interest and importance to know which set of results most nearly approximates the true condition in the lake.

The green algae were rare everywhere in June, but increased somewhat at certain stations in July and August. Few stations showed counts above one thousand per liter. This group was most abundant in September, when several stations yielded counts of about 5 thousand. At no place, even at the three stations farthest west, did the abundance approach the average of the Island Section for September (Figure 15) The common genera were Coelastrum, Dictyosphaerium, Pediastrum, and Sphaerocystis.

In June the blue-green algae were concentrated at the surface in the central basin, and were almost absent from the section east of

Long Point. Some of the surface samples showed about 6 thousand units, while at the bottom the counts were negligible. In July the group was more evenly distributed, both horizontally and vertically, but was quite rare. The central basin showed very few blue-greens in August, while east of Long Point there were several stations with counts as high as 5 thousand. In September this relationship was reversed, but few stations had high counts. At no time or place did the blue-greens approach the average abundance in the Island Section in September (Figure 15).

Making due allowance for the fact that Burkholder's records are based on net rather than centrifuge samples, the conclusion is inescapable that Western Lake Erie is much more rich in plankton (per unit of volume of water) than the part of the lake farther east.

Reighard (1894) reported that Lake Erie near the islands contained about three times as much plankton per unit of volume as Lake St. Clair. This conclusion was based on a few volumetric determinations of the total net plankton made in September. On September 23, 1930, counts were made of surface and bottom centrifuge samples taken near the outlet to Lake St. Clair. The total count was 114 thousand units per liter. The average count for the Island Section in late September - early October, 1930, was 452, or four times the count for Lake St. Clair. Both of these comparisons are based on meager data, but they justify the conclusion that Western Lake Erie is much more productive than Lake St. Clair in September. On the basis of comparisons with Apstein's work on European Lakes, Reighard considered both Lake St. Clair and Lake Erie plankton-poor lakes.

Judging by the volumetric determinations of the total plankton made by Ward (1896), Western Lake Erie is more productive than Lake Michigan in the Traverse Bay region. He found that the average volume of plankton was about the same as in Lake St. Clair, but the shallow water contained about twice as much, which still was less than the amount in Lake Erie according to Reighard's date.

Eddy's (1927) data indicate great abundance of phytoplankton in the surface water along the south shore of lake Michigan. In October, 1926, net collections at Sawyer, Michigan, and Michigan City and Dunes Park, Indiana, yielded from 18 to 71 thousand units of diatoms per liter (ignoring rare forms). Filter paper collections at Michigan City gave a count of 147 thousand units of diatoms. Greens and blue-greens were rare. In May, 1927, net collections at Gary and

Dunes Park gave counts from 128 to 193 thousand units of blue-greens and diatoms combined. At Dunes Park, filter paper collections showed 825 thousand units of blue-greens (Lyngbya), and 713 thousand units of diatoms. Even in July, when a low diatom count would be expected, net collections yielded 474 thousand diatoms per liter at Chicago. It is extremely unlikely that these counts represent the normal amount of phytoplankton in Lake Michigan, either for the lake as a whole or for the region investigated. It is a well-known fact that the lake is polluted along the heavily populated south shore, and it seems almost certain that the algae have increased greatly as a result of the raw materials for food manufacture added to the water by the domestic sewage. For that reason, it need not be concluded that Lake Michigan is more productive than Lake Erie in the Island Section.

Burkholder and Tressler (1932) made a study of the plankton of some bays at the east end of Lake Ontario in June, July, and August, 1931. Greens and blue-greens contributed very little to the plankton as compared with diatoms. Only one station had a count of more than 60 thousand units of greens per liter, and many had counts between 10 and 30 thousand units. Blue-greens were more rare than greens; the highest count was 30 thousand units, and the group was rare or wanting at several stations. Diatoms were quite abundant at all stations. The highest count was about 300 thousand units per liter, and several were as high as 120 thousand. In general, these counts are higher than those in Western Lake Erie at corresponding times of the year. However it should be noted that the bays are shallow and somewhat protected, so that they do not give us any idea of the amount of plankton in the open lake.

These few comparisons within the Great Lakes contribute little toward an answer to the question of richness of plankton in Western Lake Erie. About all that can be said with certainty is that Western Lake Erie is more productive than the rest of the lake, and that it is more productive than Lake St. Clair. From our knowledge of plankton production in inland lakes, it seems probable that Lake Erie, because of its shallowness, is the most productive of the five large lakes of the system.

Where possible, comparisons of the abundance of plankton by weight are more satisfactory than by count. Several determinations of the weight of plankton in the Island Section of Western Lake Erie were made in autumn of 1929. The method was as follows: A one liter sample of lake water was run through the electric centrifuge twice, and the plankton transferred to a silica dish. The sample was dried at 60 degrees

Centigrade for a period of 17 hours, cooled in a desiccator and weighed. It was then ignited in an electric furnace for 30 minutes, cooled, and weighed again. After correcting for the amount of dissolved material in the water transferred from the centrifuge bowl with the plankton, the loss of weight by ignition was designated as the dry organic matter of the plankton. This method involves the total plankton, that is, both animals and plants, but the plants ordinarily contribute several times as much weight as the animals.

The organic matter of the plankton was determined on eight dates from September 20 to October 22. The average amount during this period was 2,200 milligrams per cubic meter of water; the smallest was 1,800 and the largest 2,900. In Lake Mendota, for a similar period of 1915 (Birge and Juday, 1922, Figure 34), the average amount was approximately 2,130 milligrams per cubic meter, with a range from 1,660 to 2,670. In the same period of 1916 (Figure 35), the average amount was approximately 2,310 milligrams per cubic meter, with a range from 1,830 to 3,000. The two year average for the period concerned was 2,220 milligrams per cubic meter, which was almost exactly the same amount as in Western Lake Erie in the same period of 1929 (2,200 milligrams per cubic meter).

There are reasons for believing that the plankton of Western Lake Erie derives more of its organic matter from the so-called dust-fine detritus than does Lake Mendota. Western Lake Erie is frequently disturbed by winds which bring into suspension the dead and disintegrating plankters on the bottom, while in Lake Mendota many of these forms sink to the bottom and remain undisturbed during a considerable part of the period in question. That much detritus of organic origin enters the plankton of Western Lake Erie is suggested by the fact that there is much of inorganic origin. The presence of a large amount of inorganic sediment is indicated by the brick-red color of the ignited samples, and by the high percentage of ash. On the average, the ash made up 72.1 per cent of the dry weight of the plankton, and in one case it made up 82.3 per cent. In Lake Mendota, the largest per cent of ash was about 75.0, and doubtless the average was much less. Another point to be noted in comparing the two lakes is that Lake Mendota shows high phytoplankton counts. Thus in 1925, the total count in spring was about 900 thousand units per liter and in autumn was 1,100 thousand units (Domogalla, 1926). If the year 1925 was representative of normal conditions, it is obvious that Lake Mendota has much more living material in its plankton than Western Lake Erie.

According to this interpretation, Lake Mendota would be considered more productive than Western Lake Erie, even for the period when the weight of organic matter in the plankton was the same. The superiority of Lake Mendota as a producer of plankton is indicated further by the fact that its spring and autumn maxima are of similar magnitude, while in Western Lake Erie by far the most plankton is produced in autumn, when the weight determinations were made. Lake Mendota is the least productive of the Madison lakes, but all of the others except Lake Wingra are markedly affected by pollution, and Lake Mendota is probably the most nearly typical eutrophic lake of the group. Another lake of this type is West Okoboji Lake, Iowa, studied by Birge and Juday (1920). In early August, 1919, this lake yielded only 526 milligrams per cubic meter, which is less than one third of the amount in Lake Mendota for a comparable period in 1915 and 1916. West Okoboji is probably much poorer in plankton than Western Lake Erie.

It is certain that Western Lake Erie is poorer in plankton than some of the soft-water lakes of northeastern Wisconsin. The mean amount of organic matter in 81 lakes studied in July and August, when the plankton should be low, was 2,020 milligrams per cubic meter (Birge and Juday, 1927). This amount is only slightly less than that of Western Lake Erie in autumn. Ten of the lakes were very rich in plankton, with a mean of 5,570 milligrams; the mean for the remaining 71 lakes was 1,530 milligrams. It is not unlikely that Western Lake Erie would compare favorably with the average of these 71 lakes.

Green Lake, Wisconsin, is an example of the oligotrophic type of lake. In 1921, the mean weight of dry organic matter for late September - early October was approximately 658 milligrams per cubic meter (Juday, 1924, Figures 1 and 2). In 1922, the corresponding figure was approximately 1,100 giving a two year average of 880 milligrams per cubic meter for the period. The amount in Western Lake Erie during a similar period was 2,200 milligrams, or 2.5 times as much. At no time from April through November did the amount in Green Lake reach as high as 1,500 milligrams. Making allowance for the fact that some of the dead plankton of Green Lake sinks to the bottom, there is still a wide margin in favor of Western Lake Erie. Lake George, New York, also of the oligotrophic type, is probably much like Green Lake in the abundance of its plankton. In August, 1920, this lake yielded 873 milligrams per cubic meter (Juday, 1922, pp. 46-47).

Estimates of the amount of organic matter in Lakes Canandaigua, Cayuga, and Seneca, in summer (Birge and Juday, 1921, page 250), indicate that these lakes are much poorer in plankton than Green Lake.

It is clear that the abundance of plankton per unit of volume in Western Lake Erie is between that of Lake Mendota, a eutrophic lake, and Green Lake, an oligotrophic lake. These two lakes are fairly typical of their classes; the first class is generally rich in plankton, (per unit of volume) and the second generally poor (Thienemann, 1925, page 202). It is a question just what position to assign to the Island Section of Western Lake Erie in the wide range between the rich and poor lakes, but it probably stands nearer the rich end of the scale, and might be described as "moderately rich" in plankton. It has been shown that the main part of Lake Erie contains considerably less plankton per unit volume than the Island Section. The lake as a whole, then, would stand below the Island Section in the scale of richness.

In making these comparisons, only the Island Section has been considered. It will be shown later that there are pronounced irregularities in horizontal distribution in Western Lake Erie as a whole, and the available data do not permit a determination of the mean abundance for the whole area. The southwest corner of the lake is rich in plankton and the northwest corner is poor, as compared with the Island Section, so that the latter probably is fairly representative of the whole.

Portage River Section

This section of the lake was represented by a single regular station (Station 159), located 1/4 mile out from the mouth of Portage River. Because of littoral currents, and the alternate inflow and outflow of the river, conditions at this point are constantly changing. In order to determine the changes in the abundance of phytoplankton, it would be necessary to make a special investigation of this small area. In the present study, it was possible to take samples only a few times during the season, and the records are necessarily inadequate. However, they are sufficient to indicate some well-marked differences between this section and the open water of the Island Section. The figures on abundance of the phytoplankton groups for 1929 and 1930 are given in Table 55.

Table 55.- Abundance of phytoplankton groups at Station 159 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929							1930							
	May 21	June 18	July 6	July 26	Aug. 16	Sept. 24	Oct. 10	May 13	June 17	July 6	July 26	Aug. 4	Aug. 22	Sept. 2	Sept. 16
Diatoms	73	649	47	54	170	102	380	159	16	53	30	50	128	86	175
Greens	5	18	39	18	45	78	65	56	1	84	93	69	261	306	210
Blue-greens	3	0	69	27	344	180	85	8	2	67	86	296	311	391	550
Others	0	1	2	0	1	1	0	0	0	2	3	4	1	0	0
Total	81	668	157	99	560	361	530	223	19	206	212	419	701	783	935

In spite of the small number of dates on which samples were taken, it is possible to detect seasonal changes in abundance similar to those observed in the Island Section. The diatoms showed two periods of great abundance; the greens and blue-greens only one. In general, the times of abundance agreed with those in the open lake, although there were some notable differences. The most marked differences between the two sections were in the rather consistently greater abundance of all groups (especially blue-greens), and in the earlier appearance of greens and blue-greens in large numbers at the inshore station.

It seems probable that three factors have been especially important in bringing about the greater abundance as compared with the Island Section. One of the factors is shallowness of the water. Station 159 has a depth of only 3.5 meters, and the 6.4 meter contour lies at a distance of about four miles from the shore at this point. In general, the total amount of plankton in lakes of the same region varies directly with the area, and the amount per unit volume of water varies inversely with the mean depth.[6] If the area near Station 159 be considered as a somewhat distinct unit with respect to plankton production, it would be expected to have greater abundance of plankton per unit volume than the deeper water of the Island Section.

A second factor is the proximity of Station 159 to the estuary of Portage River. For a distance of about nine miles above Port Clinton the river is virtually a lake, and, being shallow, should contain an abundance of plankton. If so, the river would help to colonize Lake Erie near its mouth and keep the plankton counts higher than in the open lake. Samples taken in the river at Port Clinton on three dates in 1930 had counts not far different from those at Station 159 on the same dates.

These two factors have contributed to the natural richness of the Portage River Section. In addition there has been the stimulating effect of nutritive salts derived from domestic sewage. The general principle that increased raw material for food manufacture results in increased abundance of plankton algae is too well established to require proof here. Portage River receives domestic sewage from a number of communities and there is no doubt that the plankton algae of the estuary, and of the lake nearby, make use of the elementary nutrient materials derived from it. How great an effect pollution has had cannot be determined because nothing is known of the abundance of plankton under natural conditions.

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[6] The inverse relationship between depth and plankton production has been designated as the Law of Huitfeldt-Kaas by Naumann (1932, p. 82).

Doubtless the prominence of blue-greens in this section is due, in part at least, to pollution. This group is particularly favored by the presence of an abundance of nutrient material, and commonly thrives in polluted waters.

Maumee Bay Section

Three regular stations were located in this section: Station 250, at the mouth of Maumee River; Station 252, at Toledo Harbor range lights; and Station 254, at Toledo Harbor Lighthouse (see Fig. 1). This area was not studied for as long periods as the Island Section, and as a result, very little was learned of the seasonal distribution of the plankton algae. The available data for the seasons of 1929 and 1930 are given in Tables 56, 57 and 58.

Station 250. The depth at Station 250 was three meters in 1929, and, as a result of dredging, about six meters in 1930. However, the depth of the general area is less than two meters. At this station the physical and chemical conditions are unusually subject to change because the current of the river reverses periodically. Sometimes the water here is river water and at other times it is water from the bay. Only four samples in as many months were taken in 1929 (Table 56). Little can be gained from these few records, but it should be pointed out that the counts were not unusually large except on September 7, when the blue-greens were very numerous.

Table 56.- Abundance of phytoplankton groups at Station 250 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929				1930					
	June 26	July 17	Aug. 3	Sept. 7	July 3	July 25	Aug. 14	Aug. 28	Sept. 9	Sept. 30
Diatoms	29	0	180	150	22	87	203	123	418	406
Greens	152	20	22	90	566	765	2480	1235	1958	850
Blue-Greens	0	0	8	980	64	718	2417	1541	1665	2002
Others	0	5	2	15	0	3	20	0	0	0
Total	181	25	212	1235	652	1573	5120	2899	4041	3258

Table 57.- Abundance of phytoplankton groups at Station 252 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929					1930					
	June 26	July 17	Aug. 3	Sept. 7	Oct. 3	July 1	July 25	Aug. 14	Aug. 28	Sept. 9	Sept. 30
Diatoms	32	132	345	520	670	99	77	105	113	250	233
Greens	51	80	65	560	215	282	207	250	735	611	630
Blue-greens	0	0	95	1065	440	159	328	1220	1073	1095	1988
Others	0	2	1	15	0	1	3	7	0	0	0
Total	83	214	506	2160	1325	541	615	1582	1921	1956	2851

Table 58.- Abundance of phytoplankton groups at Station 254 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929					1930					
	June 26	July 17	Aug. 3	Sept. 7	Oct. 3	July 1	July 25	Aug. 14	Aug. 28	Sept. 9	Sept. 30
Diatoms	43	22	339	165	502	162	10	26	120	280	316
Greens	16	12	40	345	118	110	107	163	150	640	250
Blue-greens	0	3	72	516	338	47	81	169	712	1370	931
Others	0	0	1	6	0	2	0	0	2	10	0
Total	59	37	452	1032	958	321	198	358	984	2300	1497

In 1930, this station was sampled twice in each of the months of July, August and September. The changes in abundance were somewhat erratic, as one might expect from the location of the station, but the counts of the three leading groups were consistently high, with the exception of diatoms on July 3. During the period of three months, diatoms were most abundant in September, at the time of the autumn maximum in the Island Section. Presumably there was a spring maximum also, but sampling was begun too late to show it. The abundance in autumn was well above the average abundance in the Island Section in 1930 at the same time. The green algae were extremely abundant on all of the six dates; the lowest count was nearly six times as high as the maximum for the Island Section. Moreover, the greens were more abundant than the blue-greens on four of the six dates. The blue-greens became abundant later than the greens but outnumbered them in late August and late September. Both greens and blue-greens were most abundant in mid-August, rather than in September, as in the Island Section. Both of these groups were more abundant than diatoms on every date. The algae other than diatoms, greens, and blue-greens were absent on several dates, but were rather abundant on others.

The explanation for the much higher counts of 1930 as compared with those of 1929 probably is bound up, in part, with current reversals in the river. Because of the usual rarity of plankton in rivers, one would expect to find few algae at Station 250 after the current had been out of the river for a long time, and many algae after a long period of inflow. Unfortunately current direction is known only for the time of sampling, so it is not possible to determine definitely whether such a relation exists in the present case. However, on June 26 and July 17, 1929, the current was out when the samples were taken, and the total counts were lower than on August 3, when there was no current, and much lower than on September 7, when the current was upstream. The record for 1930 shows outgoing current on August 28 and September 9. The fact that high counts were recorded on those dates would not be surprising if it were known that the current had just begun to flow out after a long period of inflow. The remaining four samples were taken when the current was flowing into the river, or when there was no current. The relatively low counts in July probably are to be explained on the basis of seasonal change.

Granting that direction of current was partly responsible for the apparent difference in abundance of algae in the two years, it seems probable that there was an actual difference. This is suggested, first, by the superiority in numbers of the September, 1930, samples over that of September, 1929, even though the observations on current would indicate the reverse relationship; and second, by the rather consistently larger counts at Stations 252 and 254 in 1930 as compared with

1929 (Tables 57 and 58).

Because of the frequent and marked changes in conditions resulting from the current reversals at Station 250, it would be necessary to make a much more detailed study to determine the average abundance of phytoplankton with any degree of accuracy.

A number of investigators have found that certain species of algae are tolerant to a high degree of pollution, and that the tolerant species have considerable value as an index of pollution. Much of our present knowledge of these index organisms has been summarized by Whipple (1927). In the present investigation no attempt has been made to apply the method to the study of pollution. To do so would require a detailed study at each station in order to determine the species composition of the plankton. There was not sufficient time available for such a study. In generic composition, the plankton at Station 250 was quite similar to the plankton of the Island Section. However, there were notable differences in the relative abundance of the genera, and of the groups also. The most abundant genera of diatoms at Station 250 in 1930 were Melosira, Synedra, Tabellaria, and Stephanodiscus. The most abundant greens were Scenedesmus, Ankistrodesmus, Actinastrum, Tetrastrum, and Dictyosphaerium. The most abundant blue-greens were Aphanizomenon, Microcystis, Coelosphaerium, and Merismopedia.

Station 252. Conditions at Station 252 are less changeable than at Station 250, because of the distance from the mouth of Maumee River. The current of the river is so weak, during times of small discharge, that its effect must be largely lost before reaching Station 252. This does not mean that the water at Station 252 is unaffected by water from the river, because there must be a general movement away from the river. It merely means that the periodic reversals of current affect the station little or not at all. The depth at Station 252 is 3.9 meters, but the general area is not much more than one half as deep. Table 57 shows the phytoplankton data collected at this station in 1929 and 1930.

While the periods of time were very short, it is possible to see a trend from low counts in summer to high ones in early autumn, followed, in some cases, by a decline at the close of the season. The diatoms were more abundant than the greens or blue-greens on four of the five dates in 1929. In 1930, the diatoms were relatively rare as compared to 1929, and were outnumbered by greens and by blue-greens on every data. The greens and blue-greens were distinctly more abundant in 1930 than in 1929. One possible reason for these differences is the difference in temperature in the two years. As mentioned several times before, 1930 was a warmer season than 1929, and presumably would favor the development of greens and blue-greens, and retard the development of diatoms.

In both years the blue-greens were more abundant than the greens on most of the dates. The three dates on which this relation was reversed came in the early part of the season. The same was true at Station 254 (Table 58) and (less consistently) at Station 250 (Table 56), agreeing with the findings in the Island Section.

Comparing abundance at Stations 250 and 252, it may be seen that the counts were generally higher at Station 252 in 1929, and at Station 250 in 1930. It was pointed out previously that two of the four samples at Station 250 in 1929 were taken when the current was out of the river, whereas only two of the six samples of 1930 were taken at that phase of the current. This would account, in part, for the relatively low counts of 1929 compared (1) to those of 1930 at the same station, and (2) to those of 1929 at Station 252. It seems probable that the abundance of plankton is ordinarily greater in the area about Station 250 than at Station 252, but it is not possible to prove this statement from the available data.

Station 254. Station 254 is located well outside of the natural limits of Maumee Bay, and the conditions which prevail here are those of the open lake. The water is 6.2 meters deep. Table 58 shows the data collected here in 1929 and 1930.

In spite of the short periods of time covered, distinct seasonal trends similar to those in the Island Section are evident. In both seasons the diatoms decreased in the early part of the season, and later increased, reaching the maximum at the end of the season. The greens also declined in the early part of the season and reached their greatest abundance in early September. The early season decline was absent in the blue-greens, but they reached their maximum at the same time as the greens. In the relative abundance of these groups, the situation was similar to that at the preceding station. In 1929 the diatoms generally outnumbered the greens and blue-greens, while in 1930 this relationship was reversed. In both years, greens were more abundant than blue-greens in the early part of the season, and less abundant later. In general, the plankton was much more abundant in 1930 than in 1929.

The abundance of phytoplankton at Station 254 was less than at Station 252 on every date except September 9, 1930. The superiority in numbers at Station 252 was due largely to the greens and blue-greens, for in many cases, particularly in 1930, diatoms were more numerous at Station 254. Except for two dates in 1929, the plankton was more abundant at Station 250 than at Station 254. The total counts at Station 254 were consistently higher than the averages for the Island Section on comparable dates (Tables 51 and 53).

General Statement. The most outstanding feature of the phytoplankton of the Maumee Bay Section is the great abundance as compared with the Island Section. A second notable feature is the decline in abundance with increased distance from Maumee River. A third is the dominance of blue-green algae over greens, and of greens over diatoms, in 1930, when the most adequate data were obtained. Exceptions to all of these statements may be found in individual samples, but they appear to be true in general.

It seems probable to the writers that two factors are of especial importance in causing the great abundance of phytoplankton in this region, namely, depth of water, and abundance of nutritive materials in the water. It is well known that shallow bodies of water, in general, produce more plankton per unit volume of water than deep bodies of water of the same region. It is likely, then, that Maumee Bay was more densely populated with plankton than the Island Section even before man influenced the character of the water. It has been shown in the chapter on chemistry (p. 104) that the water of Maumee Bay contains much more nitrogen than the water of the open lake. Likewise it contains more free carbon dioxide and calcium bicarbonate. Without doubt the algae have increased greatly as a result of this added supply of raw material for food manufacture.

Scanty depth and high concentration of nutritive material will account for the great production of phytoplankton in Maumee Bay, and the same factors are involved in the diminution of production with increased distance from the river. Since the depth increases and concentration of nutritive material decreases with greater distance from the river, a decline in abundance of phytoplankton is to be expected.

The average abundance of algae in the three stations in Maumee Bay in 1930 is represented graphically in Figure 18. Curves for albuminoid and free ammonia are included in the graph to show the relationship between concentration of nitrogen in these forms and the abundance of algae. Curves for nitrite and nitrate are not shown because their concentration is not a measure of the amount available for plant use (see page 176). Figure 18 shows strikingly the marked reduction of the ammonias and green and blue-green algae with increasing distance from the river. There was little difference in abundance of diatoms at the three stations. It should be noted that diatoms were less abundant than greens or blue-greens, particularly at the most heavily polluted station, and that blue-greens were more abundant than greens at each station. The dominance of the blue-greens can be explained by the abundance of nutritive material, for it is well known that this group is particularly favored by such a condition.

Another point worthy of notice is that the phytoplankton at Station 250, 252, and 254 was more abundant in 1930 than in 1929. The cause of this difference is not known with certainty, but it appears probable that the cause was a difference in concentration of nutritive materials in the two years, which in turn was dependent upon a difference in discharge of Maumee River. It was pointed out on page 86 that in the months of July, August, and September, 1929, the mean discharge of the river was 2159 cubic feet per second, and that the corresponding figure for 1930 was only 234 cubic feet per second. If the amount of sewage entering the river remained the same, the average concentration of nutritive materials in the lower river would have been greater in 1930 than in 1929. Moreover, there would be less outflow from Maumee Bay in 1930, and hence a greater concentration in the bay.

The great abundance of plankton in this area indicates that poisonous trade wastes were not present in sufficient quantities to kill plankton organisms.

In addition to the large numbers of living algae, the water of this area contains much non-living matter of organic nature. Probably sewage is the most important source of this material. Some of it is so finely divided that it remains in suspension a long time. Waves and passing vessels tend to keep the water in motion and prevent settling out. In the centrifuge plankton samples the minute particles were quite uniformly distributed through the liquid so that estimation of the amount present was impracticable. However, this organic detritus must be an important item of food for the rotifers and crustacea of the plankton, and should be taken into account in a general way. It was much more conspicuous in this section of the lake than in any other.

River Raisin Section

The River Raisin Section is represented by only one station, Station 117, about two miles out from the shore, where the water is six meters deep. The data collected here on five dates in 1929, and on eight dates in 1930 are given in Table 59.

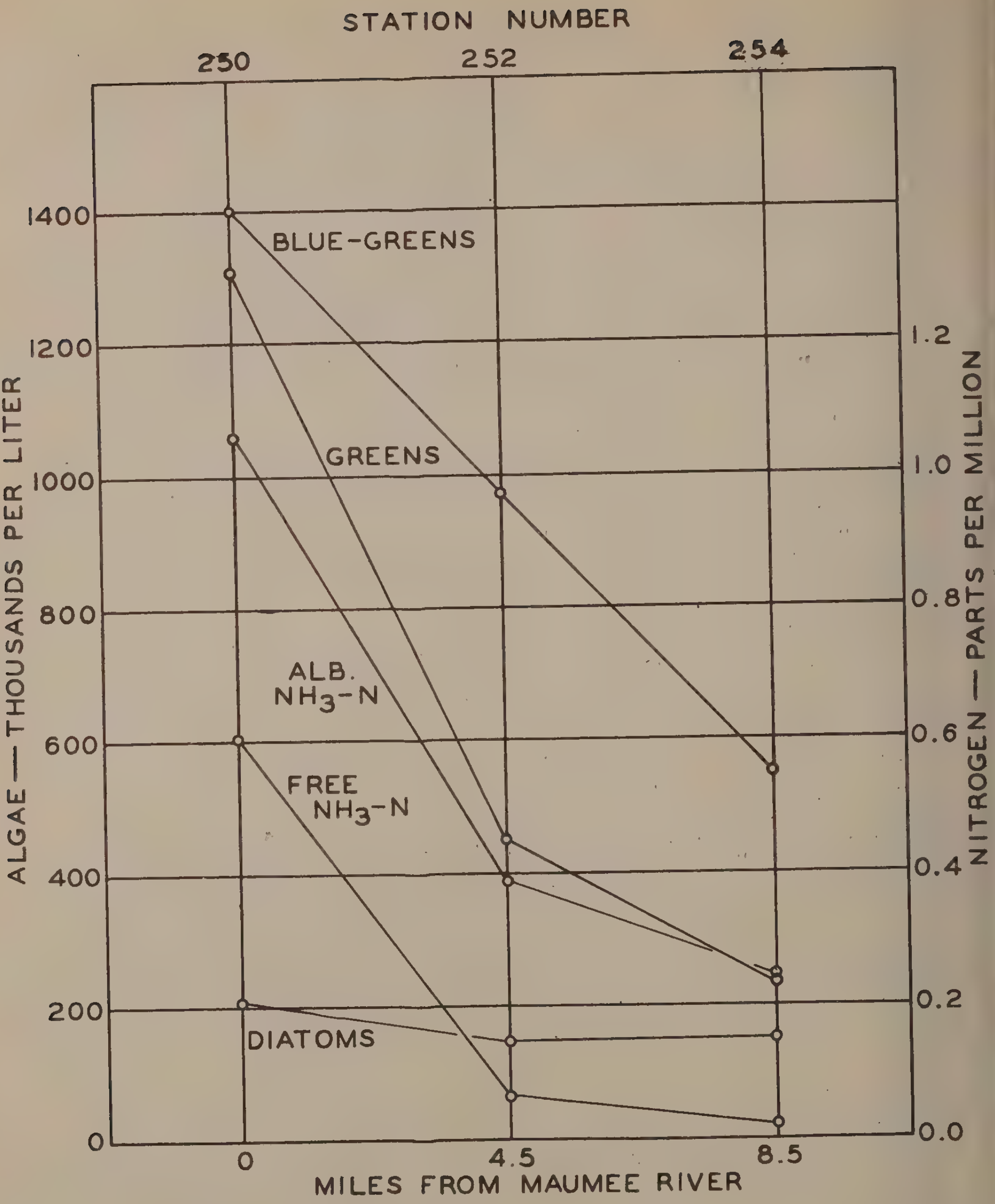

Fig. 18--Average abundance of phytoplankton groups, and of albuminoid and free ammonia, in the Maumee Bay Section in July, August, and September, 1930. Each point represents the average of six determinations. Data taken from Tables 33, 56, 57, and 58.

Table 59.- Abundance of phytoplankton groups at Station 117 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929					1930							
	June 21	July 9	July 27	Aug. 17	Oct. 16	May 27	July 8	July 30	Aug. 8	Aug. 16	Aug. 30	Sept. 11	Sept. 30
Diatoms	134	78	46	43	295	431	47	10	21	48	55	75	145
Greens	11	47	54	22	40	112	79	126	139	195	225	347	255
Blue-greens	6	4	60	197	10	32	27	214	292	591	285	925	1100
Others	1	-	-	-	-	3	1	2	1	-	1	-	-
Total	152	129	160	262	345	578	154	352	453	834	566	1347	1500

These data show some characteristics in common with those for Maumee Bay. There is some indication of seasonal changes such as those found in the Island Section, especially in the data for 1930, which are more complete than those for 1929. Also, as in Maumee Bay, the abundance in 1930 was decidedly greater than in 1929; and blue-greens were dominant over greens and diatoms, except for the first two dates in both years, and the last in 1929. Moreover the total counts at Station 117 were much higher than those in the Island Section for almost all comparable dates (Tables 51 and 53). These points in common between the Maumee Bay Section and the River Raisin Section suggest that the influence of factors involved in plankton production is somewhat the same in both.

In abundance of phytoplankton, Station 117 resembles Station 254 more closely than the stations nearer Maumee River. For a period of three months in 1930, the mean count at Station 117 was 751 thousand units per liter, and 943 thousand units at Station 254. Station 117 resembles Station 254 in depth (both about six meters), and in the concentration of nitrogen compounds (Tables 39 and 33). There is little doubt that both of these stations were naturally rich in plankton as a result of their proximity to shallow water and that this has been augmented by the addition of nutritive salts from the rivers. As in Maumee Bay and Portage River Sections, the dominance of blue-greens probably is a response to the increased amount of nutritive salts resulting from pollution.

Detroit River Section

Station 126 is located in the lake, five miles from the mouth of Detroit River. The depth is seven meters. The phytoplankton counts for this station on five dates in 1929 and six dates in 1930 are given in Table 60.

There is little evidence of seasonal change in abundance, except possibl in the increase in the samples at the end of the season. The outstanding feature of the data is the small amount of plankton. On July 9, 1929 the count of diatoms was unusually high. On page 125 it was pointed out that Station 126 was probably affected by water brought from the southwest on that date. Water from that direction would contain an abundance of plankton. Strangely enough, the count of Station 126 on July 9 was higher than the count at Station 117 (Table 59) on the same day. On June 20, 1929, the diatom count at Station 126 was higher than the average for late June in the Island Section (Table 51). With these two exceptions the counts at Station 126 were consistently lower than those in the Island Section for corresponding times of the season, and, of course, very much lower than the counts in the Maumee Bay and River Raisin Sections. This poverty of plankton in water from Detroit River is shown further by the data from Station 219, at the lower end of Bois Blanc Island, near the Canadian side of the river. The total counts in thousands of units for this station on five dates in 1930 were as follows: 70, 38, 21, 57, and 108. The average of these counts agrees closely with the average at Station 126 for the same five dates.

Table 60.- Abundance of phytoplankton groups at Station 126 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929					1930					
	June 20	July 9	July 27	Aug. 17	Oct. 16	July 10	July 23	Aug. 12	Aug. 26	Sept. 13	Sept. 23
Diatoms	82	170	11	3	75	14	13	5	6	4	34
Greens	4	28	10	1	8	9	20	19	9	34	12
Blue-greens	3	10	3	2	10	2	5	5	8	42	25
Others	1	0	1	0	12	1	1	2	2	15	0
Total	90	208	25	6	105	26	39	31	25	95	71

Plankton-poor Detroit River influences the abundance of plankton in Lake Erie for a long distance from its mouth. This is shown by the data from Station 134, located 13 miles from the mouth of the river (Table 61).

On four dates in the two years (May 27 and July 3, 1929; and July 8 and September 30, 1930) Station 134 had somewhat higher total counts than the Island Section for comparable periods of time (Tables 51 and 53). On the remaining eight dates the counts were lower than those in the island Section, and, in general, very much lower. Comparison of the data in Table 61 with those in Table 59 shows that Station 134 was very poor in plankton as compared with Station 117.

Although Station 134 is almost equally distant from Stations 117 and 126, its plankton is much more like the latter than like the former. This may be seen readily by a comparison of abundance as shown in Tables 59, 60, and 61. It is also well shown by the number of genera of green algae found at these stations in 1930. At Station 134 there were 13 genera; at Station 126, 11 genera; and at Station 117, 22 genera. Station 254 (Maumee Bay Section) yielded 19 genera. In the number of genera of diatoms, the stations were not far different, but Stations 126 and 134 had only half as many genera of blue-greens as Station 117. Thus, the stations of the Detroit River Section were poor in number of genera of algae as well as in abundance of total phytoplankton as compared with the stations near the southwest corner of the lake.

Having concluded from the data presented above that Detroit River was poor in plankton in 1929 and 1930, it seems desirable to account for its poverty. Rivers are generally poor in plankton because current is unfavorable for the organisms, but in a stream such as Detroit River, one would expect little decline in abundance during the journey from the source to the mouth.[7] That is, if the water were rich in plankton

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[7] Under certain conditions, that is, with rapid current, rough bottom, and a heavy load of sediment, plankton organisms may be destroyed by attrition. For example, Mississippi River below Rock Island Rapids carried less than 40 per cent of the amount of plankton found above the rapids (Galtsoff, 1924). Conditions in Detroit River do not appear to be favorable for mechanical destruction of the plankton.

Table 61.- Abundance of phytoplankton groups at Station 134 in 1929 and 1930. Abundance in thousands of units per liter.

Group	1929						1930					
	May 27	June 5	July 3	July 23	Aug. 8	Oct. 16	July 8	July 30	Aug. 18	Aug. 26	Sept. 4	Sept. 30
Diatoms	45	71	57	19	28	79	26	5	17	10	4	53
Greens	7	5	10	11	5	8	12	7	21	20	11	93
Blue-greens	6	2	4	1	7	5	8	10	49	10	16	422
Others	0	0	0	1	2	2	2	0	0	1	0	0
Total	58	78	71	32	42	94	48	22	87	41	31	568

on leaving Lake St. Clair, it should be rich at Station 126, unless poisonous substances derived from sewage killed the organisms. On the other hand, if the water were poor in plankton on leaving Lake St. Clair, one would expect it to be poor at Station 126.

The results of Reighard's work on the plankton seemed to point toward the second explanation, namely, that the lower river was poor in plankton because Lake St. Clair was poor. In spring of 1893 he took samples in the upper part of the river and found little plankton as compared with Lake Michigan (Reighard, 1893). In September of the same year he found three times as much plankton per unit volume of water near the islands of Lake Erie as in Lake St. Clair. A single sample in Lake Erie near Detroit River yielded less than one eighth the average amount near the islands (Reighard, 1894). Osburn (1926a) also noted the scarcity of plankton at the mouth of Detroit River.

In the present investigation it was impossible to study the situation in detail, because of the distance of Lake St. Clair from the base of operations. However, a trip was made to the lake on September 23, 1930, and samples were taken at a point near Reighard's Station VIII, where the depth was 3.9 meters. Samples at 0 and 3 meters yielded average counts (in thousands of units per liter) as follows: diatoms, 18; greens, 27; blue-greens, 66; and others, 3. These counts are very low for diatoms, greens, and blue-greens as compared with the average for the Island Section in late September (Table 53). Surface and bottom samples were taken at Station 126 about five hours after the Lake St. Clair samples. Reference to Table 60 shows that the counts of greens and blue-greens were lower than those in Lake St. Clair, while that of diatoms was higher.

It should be mentioned that the water sampled at Station 126 was not the same water sampled in Lake St. Clair, for it takes more than five hours for the water to travel from Lake St. Clair to Lake Erie. Hence, the lack of agreement in counts between the two stations is not surprising, especially since plankters may die and others may come in from marginal waters.

The evidence presented here agrees with Reighard's evidence in indicating that Lake St. Clair is poor in plankton. This conclusion, based on a study of the phytoplankton alone, as well as the total plankton (Reighard), is supported by evidence from the zooplankton alone (page 238). The results do not permit a definite statement regarding the fate of the plankton of Lake St. Clair in its travel down Detroit River, yet there are three good reasons for believing that pollution does not affect the plankton adversely. The reasons are as follows:

(1) Comparison of the counts at Station 126 and in Lake St. Clair on the same day does not point toward wholesale destruction of plankton in the river. Similar differences might be expected between two nearby stations in the same body of water. (2) There is no chemical evidence of the presence in the water of poisonous substances in such concentration that they would kill plankton organisms (page 225).7 (3) At the mouth of Maumee River, where the water was much more heavily polluted than in Detroit River, plankton was extremely abundant (Table 56).

All of the available evidence, then, leads to the conclusion that Lake Erie near the mouth of Detroit River is poor in plankton because Lake St. Clair is poor in plankton, and that pollution, if it is a factor at all, is one of minor importance.

Comparison of abundance of phytoplankton in different sections of Western Lake Erie.

In the foregoing accounts of phytoplankton in the different sections of the lake, attention was directed to relative abundance. It was shown that the Maumee Bay Section contained phytoplankton in greater abundance than the other sections of the lake. The abundance in the River Raisin Section was greater than in the Island or Detroit River Sections, but less than in the Maumee Bay Section. The Detroit River Section was shown to be poorest of all.

This relationship was particularly well shown by the data of 1930. In 1929 the program was somewhat irregular and few of the two-week periods were represented by samples from all sections. Hence, it is not possible to draw up a table showing relative abundance satisfactorily. In 1930, however, samples were taken in all sections in six consecutive two-week periods. In Table 62 the data from these samples are condensed in such a way that the abundance of total phytoplankton can be compared conveniently. For purposes of this comparison, the mean of Stations 252 and 254 is used to represent the Maumee Bay Section, because Station 250, at the mouth of the river, probably is not representative of a large area. The Portage River Section is represented by Section 159, River Raisin Section by Station 117, and Detroit River Section by Station 126. For the Island Section, the number of stations varies as indicated in Table 53, but in each case the mean of all stations visited during the period is used.

Reference to the lowermost row of figures in Table 62 shows that there were large differences in the mean abundance in the various sections. Listed in descending order with respect to abundance the sections are: Maumee Bay, River Raisin, Portage River, Island, Detroit

Table 62.- Comparison of the abundance of phytoplankton in the different sections of Western Lake Erie, 1930. Abundance in thousands of units per liter. Data taken from Tables 57, 58, 59, 55, 60, and 53.

Period	Sections and stations				
	Maumee Bay, Stations 252 and 254	River Raisin, Station 117	Portage River, Station 159	Detroit River, Station 126	Island, Several Stations
July 1-15	431	154	206	26	42
July 16-31	406	352	212	39	104
August 1-15	970	453	419	31	110
August 16-31	1452	700	701	25	155
September 1-15	2128	1347	783	95	200
September 16-30	2174	1500	935	71	544
Mean	1260	751	543	48	193

River. Moreover the different two-week periods show little change from that order. With the exception of two periods when the Portage River Section showed somewhat higher counts than the River Raisin Section, the order is the same as in the mean for all periods.

If the mean abundance in the Detroit River be assigned a value of one, the relative abundance in the other sections would be as follows: Maumee Bay, 26; River Raisin, 16; Portage River, 11; Island, 4. In other words, for the period under consideration, Maumee Bay contained 26 times as much phytoplankton as the area near the mouth of Detroit River; and similarly for the other sections. Inspection of the less regular and complete data for 1929 suggests that the order of the sections was the same as in 1930, except possibly that the Portage River Section would displace the River Raisin Section from the second position. However, it seems probable that the disparity between sections was less marked in 1929 than in 1930.

It is believed that the large and consistent differences observed in 1930 were due, in part, to natural conditions. As stated before, Maumee Bay and the lake nearby probably were very productive before man changed some of the physical and chemical conditions in that area, and there is little doubt that Detroit River is naturally poor in plankton. With the growth of large cities on tributaries of the lake, an immense amount of sewage, containing various forms of nitrogen and other compounds useful to plants, has been added to the water. The effect which this added food supply has had on the plants of the plankton cannot be determined quantitatively, but that the effect has been in the nature of an increase in abundance is hardly open to question.

It appears probable that the increases owing to pollution have tended to make more marked the natural differences in abundance between the different sections. The water from Maumee River has a higher concentration of nitrogen than that from Portage River, River Raisin, or Detroit River. Being somewhat enclosed, the water is not as rapidly diluted, and the effect on the plankton is localized. River Raisin, with lower concentration and more rapid dispersion of its waters than Maumee River, presumably has less local effect on the plankton than that river, but more than Portage River. Without doubt pollution has helped to increase the plankton near Portage River, but that area probably is naturally quite rich. Pollution in Detroit River probably has almost no local effect in increasing the plankton because of the low concentration of nutritive material in the water, and because of the unfavorable conditions imposed by the current. Presumably the plankton of the Island Section has increased as a result of pollution, both by the eastward drift of organisms produced near the river, and by utilization of the excess nutritive material not used by organisms near the rivers. The relative positions of the sections with respect to abundance of phytoplankton was the same as it was with respect to the intensity of pollution as indicated by the content of albuminoid ammonia.

Pollution has had another effect on the lake which is particularly noticeable in the water of Maumee Bay, namely, the addition of a large amount of particulate matter of organic origin. Although this material is not living, much of it is so finely divided that rotifers and crustacea can utilize it readily as food. The phytoplankton at the two outer stations in the Maumee Bay Section was 26 times as abundant as at Station 126, but this is not an accurate measure of the relative abundance of food for the animals of the plankton. If the organic detritus were added to the phytoplankton, the disparity between these two sections would be still greater. But since there was no practicable method of determining the amount of detritus in the different sections, the relative abundance of this source of food cannot be stated numerically. However, it is reasonable to suppose that the abundance of detritus, like the abundance of phytoplankton, varied directly with the intensity of pollution as indicated by the content of albuminoid ammonia.

The zooplankton of Western Lake Erie

Introduction

Previous investigations in the Great Lakes

Taxonomic and distributional studies of the plankton organisms of the Great Lakes were made years before the earliest quantitative studies of the plankton. Early reports which made important contributions to our knowledge of the crustacea were those of Smith (1874) and Forbes (1891) for Lake Superior, and Birge (1881) and Forbes (1882) for Lake Michigan. Other important papers of more recent appearance were those of Birge (1894) and Marsh (1895) for Lake Michigan, Lake St. Clair, and Lake Erie, Pearse (1910) for the state of Michigan, Sars (1915) for Georgian Bay, Bigelow (1922) for southwestern Ontario, and Eddy (1927) for Lake Michigan. Minor contributions on the subject of distribution have been made by students of fish food, such as Hankinson (1916), Wickliff (1920), Clemens and Bigelow (1922), and Pritchard (1931).

The rotifers of the Great Lakes have been made known largely through the work of Jennings, who published a number of papers on the subject. His report of 1903 refers to his earlier papers of importance. Kellicott (1896 and 1897) listed the rotifers of Sandusky Bay. Vorce (1881 and 1882) reported a large number of organisms, both plant and animal, from the Cleveland water supply. Papers on the protozoa have been noted in the chapter on phytoplankton.

Almost nothing is known of the abundance of zooplankton in the Great Lakes. Whipple (1913) made some counts of crustacea and rotifers in Lake Ontario near the mouth of Genesee River, and Eddy (1927) reported a few surface hauls from the southern part of Lake Michigan. Burkholder and Tressler (1932) presented some data on the abundance of zooplankton in four bays near the outlet of Lake Ontario, and in certain other waters connected with St. Lawrence River. The most comprehensive study of the abundance of plankton crustacea in the Great Lakes is the one carried on in Lake Erie in 1928, the results of which appear in a paper by Wilson (1929). The value of the results is largely limited by the fact that the methods employed were not strictly quantitative.

Since the completion of the present survey, a paper on the rotifers of a pond on South Bass Island has been published by Ahlstrom (1933).

Materials and methods

This paper deals with a quantitative investigation of the zooplankton of Western Lake Erie carried on in 1928, 1929, and 1930. Some work was done in each of the months of April to November, inclusive, but the most complete data were obtained in June, July, August, and September. The part of the paper which concerns the plankton in 1928 is based on 83 series of samples taken with a closing net similar to the one described by Juday (1916). With minor exceptions a series consists of two hauls, one from a depth of two meters to the surface, and the second from near the bottom to two meters. In computing the number of organisms per liter of lake water, it was assumed that the net strained one half of the column of water through which it was drawn.

In 1929 and 1930 all quantitative samples were taken with the plankton trap described by Juday (1916). The trap has a capacity of 45 liters. One hundred and five series of samples were taken in each year, which makes a total of 210 series. The total number of trap samples was 971.

It has been assumed, for practical purposes, that the trap takes a perfect sample; that it captures all of the plankton organisms which were present in the 45 liters of water before lowering the trap into position. Actually, of course, lowering the trap has a distributing influence, and the active plankters tend to move away from the center of disturbance. The lowermost part of the trap is the net, and this is at one side of the box-like part which will enclose the 45 liters. If the organisms move away from the net in all directions, the population is increased in the block of water which an instant later becomes enclosed, so that the trap captures more organisms than it should. This supposed action of the trap has not been tested experimentally, and no account has been taken of it in computing the number of organisms. In a way such action would be fortunate, for in all subsequent handling of the sample there is a tendency to lose plankton. However, this advantage would be offset by the fact that the active plankters would be increased relative to the more passive ones.

In taking a surface sample the trap was lowered just far enough to submerge it completely, and since the height of the effective part of the trap was 50 centimeters, the sample would be a sample of the plankton in the upper half meter of water. In taking a sample at 2 meters, the bottom of the trap was lowered to that depth; hence the sample would represent the layer between 2 meters and 1.5 meters. After the water had strained through the net of No. 12 bolting cloth, the catch was washed into the plankton bucket at the bottom, and then transferred to a three ounce bottle.

Because of the lack of uniformity in vertical distribution of the plankton, it was necessary to take samples at several depths to obtain an accurate average for a station. The distance between samples in a vertical series was ordinarily 2 meters, but in many cases it was 3 meters. Only two series in which the interval was 4 meters have been used in this report. The question arises: should samples have been taken at more frequent intervals to avoid errors due to differences in abundance at different levels? Table 63 was designed to facilitate a

Table 63.- Comparison of the mean number of zooplankters determined by samples taken at two meter intervals with the mean number determined by samples taken at four meter intervals. Data derived from Table 67. Means stated in numbers of individuals per liter.

Plankter	Date, and interval between samples in meters									
	April 5		May 26		June 20		July 9		July 18	
	2	4	2	4	2	4	2	4	2	4
Diaptomus	1	1	14	12	8	7	8	8	10	7
Cyclops	0.2	0.2	9	8	7	7	6	6	7	6
Nauplii	14	15	26	26	28	31	17	17	21	22
Daphnia	0.0	0.0	5	4	4	4	2	2	2	1
Rotifera	22	24	9	9	29	23	4	6	4	4

comparison of results based on samples taken at 2- and 4-meter intervals. These data were derived from Table 67, which shows the vertical distribution of zooplankters at Station 37A on several dates in 1930. On five dates, samples were taken at 2-meter intervals, giving a total of seven samples for a series. The mean number per liter of each kind of plankter was determined first from this series and then from the samples taken at 0.5, 4, 8, and 12 meters only. The 25 pairs of means are shown in Table 63.

In 12 of the 25 pairs of means the result was identical for the 2-meter and 4-meter series. In 7 pairs there was a difference of one; in 3 there was a difference of 2; in 2 a difference of 3; and in one a difference of 6. Considering the various sources of error involved in the determination of the number of plankton organisms, it may be said that the two methods gave essentially the same results. That is, the conclusions regarding mean abundance at Station 37A on the dates in question would be the same whether the mean was determined by a series of 7 samples or by a series of 4 samples. The data presented in Table 63 establish the adequacy of the series with 4-meter intervals as compared with the series of 2-meter intervals, but not the adequacy of the series with 2-meter intervals themselves. However, it may be argued that, if the vertical distribution was such that means determined from samples taken every 4 meters were essentially the same as means determined from samples taken every 2 meters, it is highly improbable that a further decrease in the distance between samples would have affected the results materially. It is safe to conclude, then, that the routine procedure of determining the mean number of plankters from samples taken at intervals of 2 or 3 meters was adequate for the purposes of this report.

Ordinarily the catch was made up to 45 cubic centimeters, and since the volume of the trap was 45 liters, each cubic centimeter in the bottle was equivalent to 1 liter of lake water. If the catch happened to be very meager, it was concentrated to a smaller volume. Very often it was desirable to combine two or more samples in one bottle. In such cases 1 cubic centimeter would represent two or more liters of lake water. Samples for counting were taken by means of a 1 cubic centimeter piston (Stempel) pipette. The sample was placed in a watch glass, transferred to a glass plate by means of a medicine dropper, and counted under a binocular microscope. In routine procedure two 1 cubic centimeter samples were counted separately, and the number of organisms was computed from the mean. Whenever there was pronounced lack of agreement in the counts of the two samples, one or more additional samples were counted.

There are several sources of error in the series of events between taking the trap sample and recording the number of plankters and the total effect of the errors is to reduce the final count. For example, in transferring the catch from trap to bottle there is an opportunity to lose organisms but none to gain them. Possible errors in making the catch up to volume tend to cancel, but in actual enumeration, there is a greater chance of overlooking an organism than there is of counting it twice. Moreover, in taking a sample with the piston pipette, some organisms adhere to the sides and neck of the bottle, and thus are not taken. Without doubt the most important source of error is the failure of the piston pipette to take an absolutely representative sample of the contents of the bottle. This error probably depends largely on the fact that the organisms cannot be distributed with exact uniformity in the bottle. The accuracy of this part of the method has not been determined. A few preliminary experimental counts with known concentrations of organisms indicated that the accuracy varies with the concentration, and since it probably is different with different organisms, the number of counts necessary to solve the problem would be very great.

An idea of the precision of the method, that is, the degree of similarity of duplicate samples from the same bottle, can be gained by examination of the data in Tables 64, 65, and 66. Table 64 shows counts of duplicate samples from each of four bottles containing plankton from four depths at Station 158. Tables 65 and 66 show a number of duplicate counts on composite samples from Station 117 and 134. At these stations the individual samples of a vertical series were combined in one bottle for counting.

Inspection of the many pairs of counts shows that, in general, the absolute difference between the two counts of a pair increases with an increase in the number of organisms in the pipette sample, but that the percentage deviation from the mean decreases. It is advantageous, then, to have the catch highly concentrated in the sample bottle. However, to bring the rare forms to the proper concentration would result in such high concentration of the abundant forms as to lengthen unduly the time required in making the count. Most of the pairs of counts in the tables show close agreement. The principal exception is in the first two counts at Station 117 on August 30. In these samples the lack of agreement for Cyclops and Bosmina was so striking that a third count was made. It appears that, whatever the accuracy of the method may be, it gives fairly consistent results. In the opinion of the writers, the agreement shown by the pairs of counts given, and by many others at hand, is sufficiently close to validate the routine procedure of making two counts, particularly since

Table 64.- Comparisons of duplicate 1 cubic centimeter samples of zooplankton taken with a piston pipette. Plankton from 4 depths at Station 158, June 11, 1930

Plankter	0 meters		3 meters		6 meters		9 meters	
Diaptomus	1	---	---	---	1	2	3	1
Cyclops	10	8	19	23	27	23	23	19
Nauplii	9	15	13	10	12	17	21	18
Daphnia	1	3	8	12	8	6	10	12
Bosmina	1	1	4	6	6	7	7	4
Rotifera	7	5	5	3	11	9	5	2

Table 65.- Comparisons of duplicate 1 cubic centimeter samples of zooplankton taken with a piston pipette. Plankton from Station 117 in 1930.

Plankter	July 29		August 7		August 30			September 12		September 29	
Diaptomus	5	8	4	7	3	---	4	2	3	1	4
Cyclops	35	42	80	73	45	23	41	46	52	21	26
Nauplii	96	89	29	38	160	176	166	12	15	7	6
Daphnia	29	23	37	34	6	8	9	10	7	4	6
Bosmina	12	7	33	35	3	14	8	4	2	—	1
Rotifera	118	109	37	31	9	8	7	6	5	1	2

Table 66.- Comparisons of duplicate 1 cubic centimeter samples of zooplankton taken with a piston pipette. Plankton from Station 134 in 1930

Plankter	July 8		July 30		August 18		September 4		September 29	
Diaptomus	2	4	6	8	---	---	1	1	2	1
Cyclops	3	3	41	40	8	8	16	13	33	20
Nauplii	13	9	47	56	30	25	4	5	24	22
Daphnia	—	—	2	—	7	4	--	2	10	9
Bosmina	3	4	3	—	4	6	1	2	—	1
Rotifera	30	22	8	5	38	35	1	2	1	—

these were supplemented by one or more additional counts when the agreement was not close.

In 1928, only the adult crustacea of the plankton were counted, and no record was made of the nauplii and rotifers. In 1929 nauplii, but not rotifers, were counted; and in 1930 both were counted. The more complete counts of 1930 were made possible by combining many of the series in one sample for each station.

Data and discussion

Qualitative Data

The rotifers were not studied to determine the species present. In 1929, the plankton crustacea were identified by Dr. Stillman Wright; in 1930, this was done by the late C. Dwight Marsh, and the identifications of cladocera were checked by Dr. J. P. Visscher, Western Reserve University. Rather than present a complete list, only the more important species are mentioned in the following summary, which was taken almost without change from a report prepared by Dr. Marsh.

The crutacean fauna of Western Lake Erie is, in many respects, intermediate in character between that of the deeper Great Lakes and smaller bodies of water. Of the species of Diaptomus in the deeper Great Lakes, the common forms are *D. sicilis*, *D. minutus*, and *D. ashlandi*; *D. oregonensis* is present, but is not common. In Western Lake Erie *D. oregonensis* is the prevailing form of this genus; *D. sicilis*, *D. minutus*, and *D. ashlandi* are found, but are not in great numbers. *D. siciloides* is not reported from the other Great Lakes, but is fairly common in pools and small lakes; apparently in Lake Erie it is not characteristic but occurs because of the connection of Lake Erie with small bodies of water. Its appearance in the lake seems to be accidental.

The plankton all over the area examined is quite uniform in its characteristics. The only difference is that in localities near shores there may be sporadic introduction of species from potamoplankton or heleoplankton, as for example *Diaptomus siciloides* and a number of the Cladocera. This does not mean a quantitative uniformity, however.

Cyclops americanus and *C. Brevispinosus* are found in Western Lake Erie in considerable numbers. Generally speaking *C. americanus* is characteristic of small bodies of water; *C. brevispinosus* is most frequently limnetic in habitat.

The characteristic Cladocera are the *retrocurva* form of *Daphnia pulex parapulex*, *Leptodora kindtii*, *Diaphanosoma leuchtenbergianum*, and

Bosmina longirostris, Daphnia being the most important.

The collections in the western end of Lake Erie show distinct changes in the composition of the plankton during the course of the year. The picture is incomplete because of the small numbers of winter collections. As far as can be ascertained from the present collections the succession of forms is as follows:

From January to March there is little change. The Crustacea present during these three months are *Diaptomus minutus*, *D. sicilis*. *D. ashlandi*, *Cyclops bicuspidatus*, and *Limnocalanus macrurus*. Diaptomus forms the major part of the collections. Limnocalanus and *Cyclops bicuspidatus* are present in immature forms. It is probable that more complete collections would show the presence of larval Epischura, although none of this species was found.

In April the winter species persist and in addition Epischura, *Diaptomus oregonensis*, *Cyclops americanus*, and the Cladocera *Bosmina longirostris*, and *Daphnia pulex pulex*. The Cladocera appear first in enclosed areas and are abundant nowhere until May. *Cyclops bicuspidatus*, which was present in small numbers and in larval form, becomes abundant.

In May there are added to the species of April *Cyclops leuckarti* in large numbers and the Cladocera *Daphnia* (*retrocurva*) and *Diaphanosoma leuchtenbergianum*. Late April is a transition period and in May the full summer fauna is established.

During June, July, and August the fauna has the same composition as in May, the prominent species being *Diaptomus oregonensis*, *Cyclops leuckarti*, *Epischura lacustris* and the Cladocera, especially *Daphnia* (*retrocurva*). *Cyclops bicuspidatus* becomes less abundant after June. *Diaptomus minutus* is more abundant in summer than at other seasons. *Cyclops prasinus* appears in August; this species has some significance, but is never present in any considerable numbers.

The September fauna is much like that of the summer months, but *Diaptomus sicilis* and *Diaptomus ashlandi* have disappeared.

In October the only abundant cladoceran is *Daphnia* (*retrocurva*); *Diaphanosoma leuchtenbergianum* and *Daphnia pulex pulex* have disappeared, and *Leptodora kindtii* is no longer prominent. *Cyclops americanus* has disappeared.

In November there is a great change and the rather meager crustacean fauna contains only *Epischura lacustris*, *Diaptomus oregonensis*, *Cyclops bicuspidatus*, *Daphnia (retrocurva)*, and *Bosmina longirostris*. Of these the only one present in any considerable numbers is *Diaptomus oregonensis*.

In December the Cladocera have entirely gone and the fauna consists of *Diaptomus oregonensis*, *D. minutus*, *Limnocalanus macrurus*, and a few immature *Cyclops bicuspidatus*.

In this series of seasonal changes, the transition from the restricted fauna of the winter to the abundance of summer and from summer conditions to winter again is quite sudden, and we can almost think of the fauna as having two seasons with the transitional months of April and November.

Quantitative Data
Island Section

Horizontal Distribution

Since plankton was first studied the question of the horizontal distribution of plankton organisms has been a controversial one. Prior to 1892, according to Apstein (1896, p. 51), it was generally held that the plankton of fresh water was not uniformly distributed over wide expanses, but occurred in swarms in some parts of a lake and only sparingly in others. Apstein believed that this conception arose from the use of nets which were hauled horizontally. By the use of vertical nets of the Hensen type, he was able to show that the plankton of the Holstein lakes was distributed with a high degree of uniformity. Since that time many students of the plankton have attacked the problem. Some of those who have discussed it at length are Reighard (1894), Ward (1896), Birge (1898), Marsh (1903), Moberg (1918), Bayersdoerfer (1924), Southern and Gardiner (1926), and Wilson (1929).

Without discussing the findings of each writer, it may be said that those who studied the volume of the total plankton (plants and animals) were impressed by the essential uniformity of distribution. There has been less agreement among the students of the zooplankton, and the last four papers cited emphasized the great inequality of distribution of the crustacea. It should be noted, however, that Moberg, and Wilson, employed methods which must be regarded as inadequate for the problem in hand. Most of Moberg's data were based on

500 cubic centimeter samples. Samples of that size would be expected to show inequalities in distribution. Wilson's data were based entirely on horizontal hauls and hence their adequacy is open to serious question. Southern and Gardiner, in a series of carefully planned experiments involving both vertical and horizontal hauls, were able to show marked irregularity in the distribution of the crustacea of Lough Derg. However, they called attention (p. 144) to a number of special conditions which tend to operate against uniform distribution in that lake. Somewhat similar conditions exist in Bodensee, studied by Bayersdoerfer.

Even the most confirmed proponents of the idea of uniform distribution do not argue for absolute uniformity, and no one expects to determine the number of organisms per unit volume with absolute accuracy. While Birge (1898, pp. 366-375) was able to show irregularities in distribution and to observe swarms with the unaided eye, his data on seasonal distribution show such regular trends and such close agreement in the different years for certain forms that there is no doubt regarding their adequacy. His results prove that it is easily possible, for Lake Mendota, and probably for most inland lakes, to take samples frequently enough to eliminate the errors arising from unequal distribution.

Large and consistent inequalities in horizontal distribution were found between the different sections of Western Lake Erie, as will be pointed out in later pages. There were also inequalities noted within the Island Section but they appeared to be fortuitous. It appears unnecessary to present the available data on horizontal distribution in this section of the lake. An attempt was made to avoid errors from that cause by taking samples from several stations rather than from one. The adequacy of the sampling program will be discussed in later pages.

Vertical distribution

Lack of uniformity in the vertical distribution of plankton organisms was noted very early, even before the introduction of Hensen's quantitative methods. It was noted also that certain of the crustacea were more abundant at the surface at night than in the day-time, indicating a diurnal vertical migration. A review of this subject has been published by Kikuchi (1930). In the present investigation, all of the samples were taken during the day-time, and hence the data are incomplete with regard to vertical distribution. Because of this incompleteness, it has been considered sufficient to present only a small part of the available data; enough to show the usual distribution of the more important plankters in the day-time, and some of the variations encountered. In Table 67 are shown all of the data taken at Station 37A in 1930 for Diaptomus, Cyclops, nauplii, Daphnia, and Rotifera.

The data presented in Table 67 need not be discussed in detail. The following summary, based on these and many other data, should suffice. During the day-time the leading groups of adult plankton crustacea (Diaptomus, Cyclops, and Daphnia) usually avoid the upper half meter of water, and concentrate in the middle depths; they are usually rare near the bottom but less rare than at the surface. The nauplii are much less consistent in their distribution than are the adult copepods. In general they appear not to avoid the upper water; but frequently they are found in largest numbers near the bottom. In a large number of cases they are found concentrated at more than one level. The rotifers also are inconsistent and often show concentration at more than one level. The remaining groups of plankton organisms are too rare to permit a positive statement with regard to their vertical distribution.

Seasonal distribution

Season of 1928

Plankton studies with the vertical closing net were begun on May 14 in 1928, and discontinued on November 20. No samples were taken during the last two weeks of August or the first two weeks in September. The samples were taken at a large number of stations which were well distributed over the Island Section. The results will be discussed in less detail than those of 1929 and 1930 because they were obtained with a relatively unreliable type of apparatus, and because of the break in the record during late August and early September.

Seasonal distribution of the four principal groups (Diaptomus, Cyclops, Daphnia, Diaphanosoma) is shown in Table 68. Each month of the period studied was divided into two periods of approximately two weeks, with minor exceptions noted in the first column of the table. The mean date of sampling for each period is given in the second column. The third column gives the number of stations used in determining the mean number of organisms for each period.

Table 67.- Vertical distribution of crustacea at Station 37A in 1930. Abundance in individuals per liter

Plankter	Depth, meters	Apr. 5	Apr. 21	May 7	May 26	June 5	June 20	July 9	July 18	Aug.5	Aug.25	Sept.6	Sept.19	Oct.2
Diaptomus	0.5	0.8	0	2	2	1	0.8	1	0.5	3	0	0	0.8	0
	2	-0	--	4	22	--	0.2	0.4	0	--	--	--	--	--
	3	--	--	--	--	7	--	--	--	3	0	0	0	0
	4	0.4	4	5	17	--	5	2	2	--	--	--	--	--
	6	1	--	--	14	18	9	4	29	3	1	4	2	0
	9	--	--	--	--	[illegible]	--	--	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4
	10	0	--	--	10	--	6	2	0.4	--	--	--	--	--
	12	0	0	0	6	0	0	0.2	1	2	2	5	3	4
Rotifera	0.5	21	11	25	9	7	21	0.5	0	0.8	2	2	9	34
	2	15	--	36	17	--	8	0.8	3	--	--	--	--	--
	3	--	--	--	--	10	--	--	--	6	4	2	6	34
	4	26	16	21	11	--	22	3	5	--	--	--	--	--
	6	22	--	--	9	41	37	5	5	6	2	6	6	22
	8	28	21	16	6	--	43	18	5	--	--	--	--	--
	9	--	--	--	--	13	--	--	--	4	2	4	15	10
	10	24	--	--	4	--	66	3	7	--	--	--	--	--
	12	20	17	27	9	16	7	0.8	4	2	3	6	9	8

Table 68 .- Seasonal distribution of the plankton crustacea in the Island Section in 1928.
Abundance in individuals per liter

Period	Mean date	No. of stations	Diaptomus	Cyclops	Daphnia	Diaphanosoma
May 14 - 13	16	6	6	5	0.7	0.2
May 21 - 25	23	7	12	23	4	0.4
June 1 - 15	11	7	7	9	11	0.2
June 16 - 30	22	11	4	4	7	0.4
July 1 - 15	9	5	18	10	13	2
July 16 - 31	28	6	9	7	3	4
August 1 - 17	12	6	8	5	1	2
Sept. 16 - 30	26	2	1	2	0.9	0.2
October 1 - 15	3	7	5	2	2	0.1
October 15 - 31	29	5	2	1	1	0.2
Nov. 1 - 15	7	3	0.5	0.6	0.4	0.0
Nov. 16 - 31	20	3	1	1	0.7	0.1

The available data indicates that Diaptomus had two periods of abundance, one in late May, the other in early July. During the period May 14-19, the mean for the area was 6 per liter. The number increased rapidly in the next few days to 12 per liter. During June the count decreased to 4 per liter, but in early July increased to 18. Thereafter (with the possible exception of the two periods for which no data are available) the counts were low, and in November, Diaptomus was present only in traces.

The seasonal distribution of Cyclops was similar to that of Diaptomus. It had two periods of abundance and these coincided with those of Diaptomus. In the early period of abundance, Cyclops was the more numerous; in the second Diaptomus was more numerous. The mean number for the season was the same for both (6 per liter).

Daphnia also had two periods of abundance. The first came in the period following the first period of abundance for Diaptomus and Cyclops, but the second period of abundance came at the same time for all three genera. At times Daphnia was more abundant than either of the others, but never more abundant than the two combined. Thus the plankton was dominated by copepods. During and after late September, Daphnia was very rare.

Diaphanosoma was a consistent member of the plankton, but never became very abundant. It appeared in largest numbers (4 per liter) in late July. During most of the season there was less than 1 per liter. Epischura and Limnocalanus appeared only occasionally. In a few samples Epischura had a count in excess of 1 per liter, but the mean for the section was always low. Another rare form was Bosmina; it disappeared during late July and early August and never had a mean count of more than 1 per liter. Leptodora was even more rare than Bosmina; during 4 of the 12 periods no specimens were taken.

It is clear from this brief discussion that the bulk of the plankton crustacea was contributed by three members, Diaptomus, Cyclops, and Daphnia. Diaphanosoma and Bosmina were present most of the time but never in large numbers. Epischura, Limnocalanus, and Leptodora were present occasionally in small numbers. It was distinctly a copepod plankton. It is worthy of note that all of the crustacea were rare in the month of November. Data for this month were not obtained in 1929 and 1930.

Season of 1929

In 1929 plankton studies were begun May 20 and discontinued October 22. All samples were taken with the plankton trap. Samples were taken from the following stations: 18, 37A, 59A, 82, 8F, 158, 68, and 75. The location of these stations may be seen in Fig. 1. The results are given in Table 69, which is made up on the same plan as Table 68. The data on Diaptomus, Cyclops, Daphnia, and nauplii are shown graphically in Fig. 19.

Table 69 .- Seasonal distribution of the plankton crustacea in the Island Section in 1929. Abundance in individuals per liter

Period	Mean date	No. of stations	Diaptomus	Cyclops	Nauplii	Daphnia	Diaphanosoma
May 16 - 31	25	11	4	5	14	0.6	0
June 1 - 15	9	7	5	10	15	8	0.01
June 16 - 30	23	8	8	6	20	12	0.2
July 1 - 15	12	7	19	7	23	2	0.8
July 16 - 31	25	3	14	7	32	7	2
August 1 - 15	5	4	12	5	11	4	3
August 16 - 31	21	8	12	7	25	3	3
Sept. 1 - 15	8	7	7	7	13	3	2
Sept. 16 - 30	25	7	4	5	12	2	0.8
October 1 - 15	9	1	3	3	5	0.4	0
October 16 - 31	20	2	1	0.4	3	0.4	0
Mean May 16 - Oct. 15	—	--	9	6	17	4	1

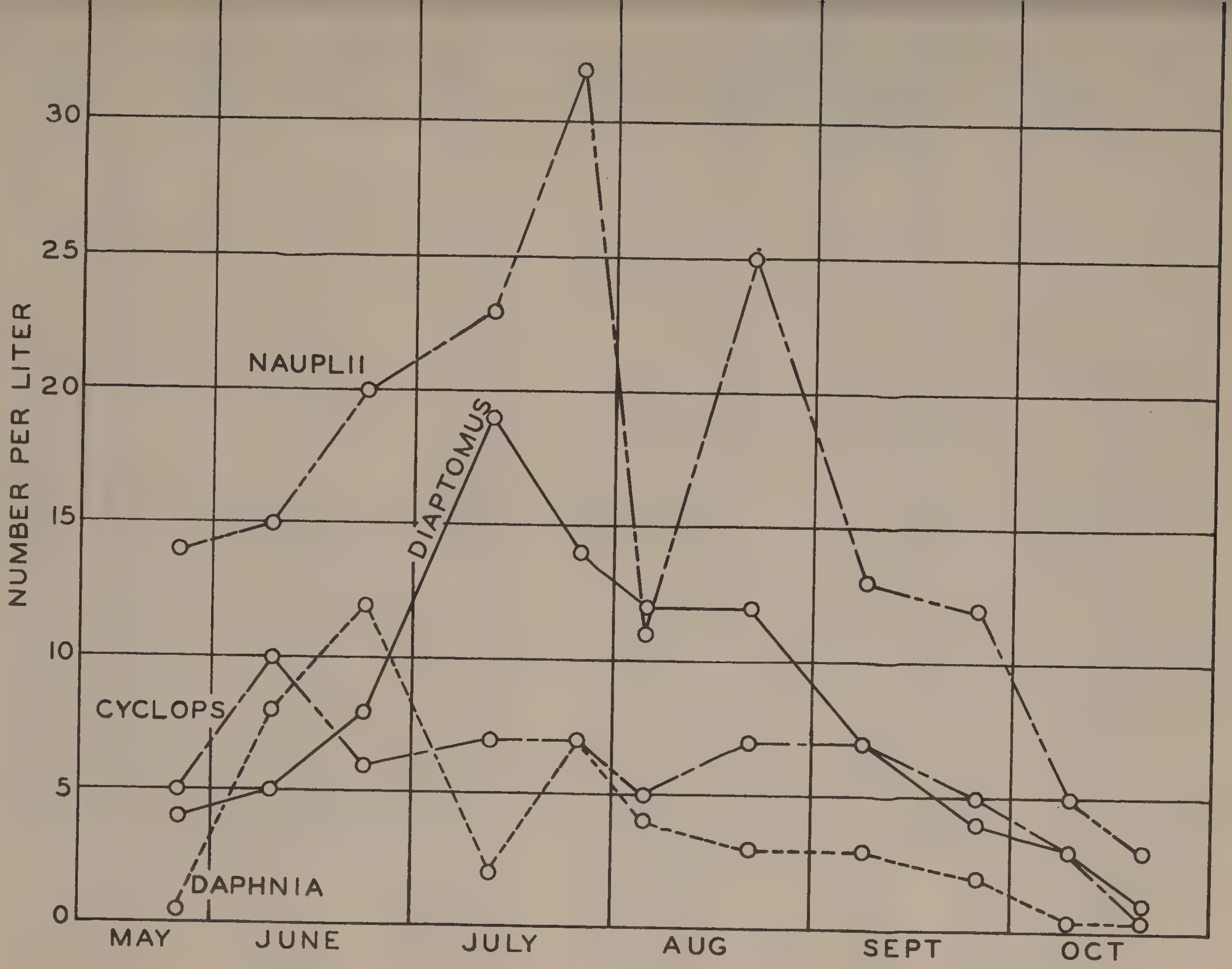

Fig. 19--Seasonal distribution of plankton crustacea in the Island Section, 1929. Data taken from Table 69.

Diaptomus was the most abundant adult form in the plankton of 1929. In late May there was an average of 4 individuals per liter. The number increased slowly in June, but rapidly in early July to the maximum for the season of 19 per liter. There followed a sharp decrease in the last part of the month. In August the abundance was maintained at 12 per liter. After that the number gradually decreased to a minimum of 1 per liter for late October. Thus, Diaptomus presents a remarkably regular curve with low points in spring and fall, and the high point in summer.

Cyclops was a less important constituent of the plankton than Diaptomus. They were about equally abundant in late May, but Cyclops increased more rapidly, reaching its maximum of 10 per liter in early June. By late June it had decreased to 6 per liter and varied little from this number until October. Like Diaptomus, it reached its minimum at the end of the season.

Daphnia was less abundant than either Diaptomus or Cyclops, on the average, although it reached a higher maximum than the latter. In late May Daphnia was rare but increased to a high of 12 per liter in late June. The period of abundance was short, however, for by early July it had decreased to 2 per liter. The count for late July indicates a second period of increase, followed by a gradual decline to the minimum for the season in October.

Thus, the three important groups of adult crustacea reached their maxima in rapid succession: Cyclops in early June, Daphnia in late June, and Diaptomus in early July. Diaptomus was so much more numerous than the other two that it determined the time of maximum for the three combined. This came in July when the combined count was 28 per liter for both periods of the month.

Diaphanosoma can scarcely be regarded as an important plankter in 1929, for its season was short and it never became numerous. It appeared in traces in early June but remained below 1 per liter until late July. The maximum of 3 per liter was reached in August, and the form had disappeared by early October.

The copepod nauplii composed the most important group numerically. The average number for late May was 14 per liter. This average figure masks an important point in connection with their probable abundance earlier in the season. Table 69 shows that 11 stations were averaged together for late May. Three of the 11 were actually second series taken at 3 of the 8 stations. The first time the 3 stations were sampled they showed an average of 18 nauplii per liter, and the second time an average of 11 per liter. This would seem to indicate that the nauplii had been abundant earlier in the month and were on the decline. The importance of this will appear later. The nauplii increased rapidly in June and July, reaching a maximum of 32 per liter for the season in late July. There was a sharp decline to 11 per liter in early August, followed by an increase to 25 per liter. Thereafter they waned and reached a minimum for the season in late October.

The genera Limnocalanus, Epischura, Bosmina, and Leptodora appeared in comparatively insignificant numbers. Limnocalanus was extremely rare. It was absent from 3 of the 8 stations, and appeared nowhere after May. The highest count recorded for any station was 0.2 per liter. Epischura was present in small numbers throughout the season. The highest counts at any station were 2 per liter; these occurred in June, July, and August. At no time did it average 1 per liter for the whole section. Bosmina was the most abundant of the four genera mentioned. It was present in small numbers in late May, increased somewhat in June but almost disappeared in late July and early August. A second period of increase followed, and judging from three series taken in October, it was increasing when sampling was discontinued. The highest count recorded was 7 per liter but it was usually less abundant than 1 per liter. Leptodora was taken frequently from June through September but it never attained abundance of 1 per liter.

Season of 1930

Plankton studies were begun April 4 in 1930 and discontinued October 3. The results obtained are shown in Table 70, and partially in Fig. 20.

In early April Diaptomus was present in small numbers and increased only slightly to 2 per liter by late April. In early May it had increased to 9 per liter, and reached a maximum for the season (10 per liter) in late May. The count for early June was reduced to 4 per liter but increased in late June to 8 per liter. Thereafter Diaptomus declined, and in August and September was an unimportant member of the plankton. Thus there were two periods of abundance, the first in May, the second in late June - early July.

Cyclops increased somewhat more slowly than Diaptomus in April and early May, but by late May it was the more abundant of the two. It continued to increase in June, reaching a minor peak of

Table 70 .- Seasonal distribution of zooplankters, in the Island Section in 1930. Abundance in individuals per liter

Period	Mean date	No. of stations	Diaptomus	Cyclops	Nauplii	Daphnia	Diaphano-soma	Rotifera
April 1 - 15	4	2	1	0.6	10	0	0	20
April 16 - 31	20	2	2	1	32	0	0	11
May 1 - 15	9	6	9	6	37	0.3	0.02	23
May 16 - 31	23	5	10	12	21	4	0	8
June 1 - 15	7	6	4	14	26	6	0	15
June 16 -30	24	6	8	17	24	10	0.3	25
July 1 - 15	12	3	7	11	20	4	1	2
July 16 - 31	21	3	5	15	17	2	1	3
August 1 - 15	4	6	2	34	17	4	6	2
August 16 - 31	22	6	0.5	16	9	3	3	2
September 1 - 15	5	5	0.8	12	10	4	2	2
September 16-30	19	6	1	10	4	4	0.6	4
October 1 - 15	2	6	2	7	4	2	3	5
Mean May 16 - Oct. 15	—	—	4	15	15	4	2	7

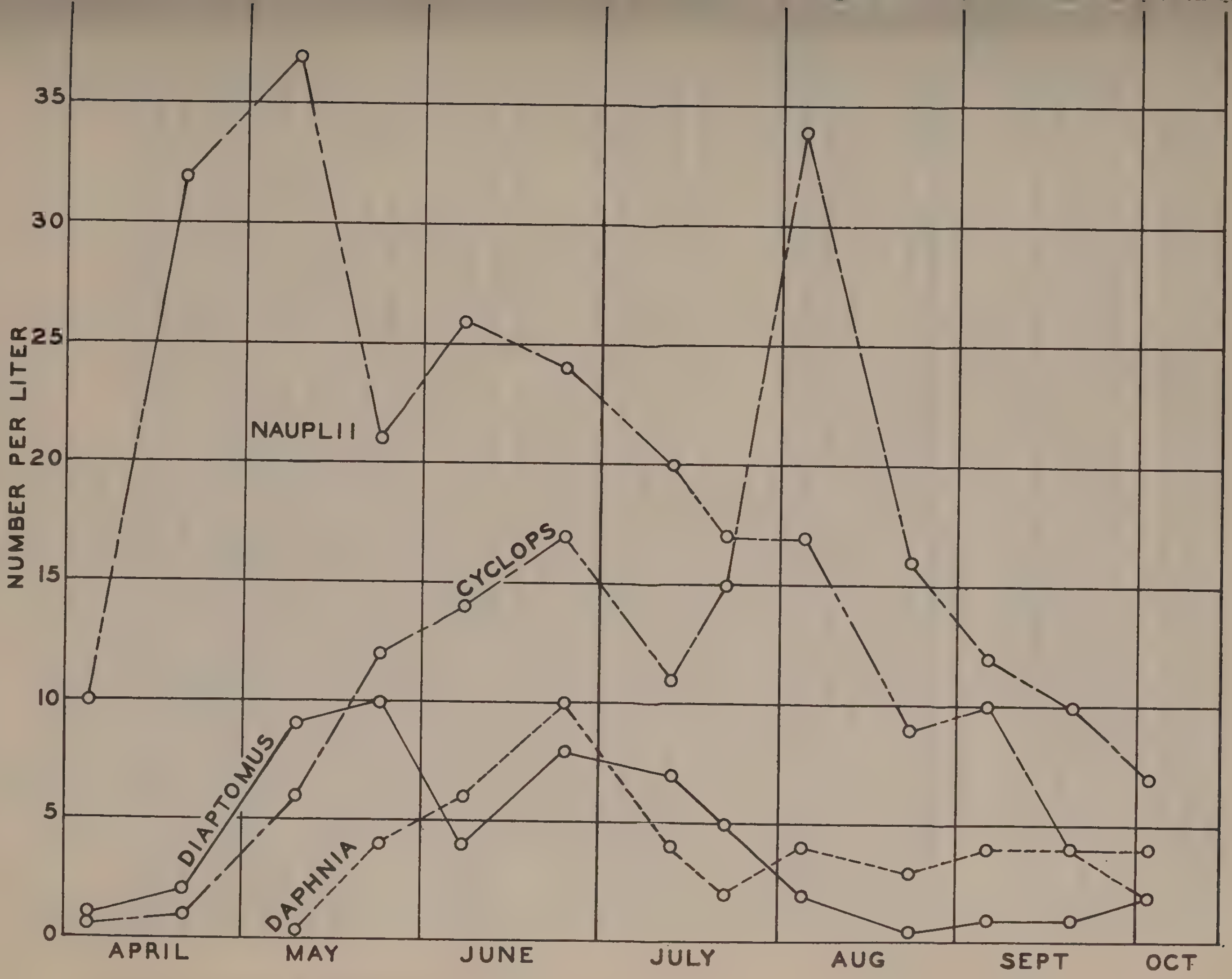

Fig. 20-- Seasonal distribution of plankton crustacea in the Island Section, 1930. Data taken from Table 70.

17 per liter in the latter part of the month. It declined to 11 per liter in early July, but soon began to increase, reaching the season's maximum of 34 per liter in early August. By late August the number had decreased to 16 per liter, and it continued to decrease to 7 per liter in the early days of October. Cyclops thus had two periods of abundance, a minor one in late June, and a period of great abundance in early August. The first period of abundance coincided with the second of Diaptomus; the second came when Diaptomus was declining toward the season's minimum.

Daphnia first appeared in the quantitative samples in early May. It increased rather rapidly and uniformly to the maximum of 10 per liter in late June. During July it decreased, reaching a low count of 2 per liter in the latter half of the month. In early August it increased again to 4 per liter and remained almost uniform until the decline of early October. The increase of early August over late July is so small that there is some question whether it should be regarded as a real increase. This point will be referred to when the two years are compared.

The nauplii were rather rare in early April but increased rapidly during the month, and continued to increase to the season's maximum of 37 per liter in early May. By late May they had decreased to 21 per liter, but in early June the count recovered to 26 per liter. Thereafter the nauplii declined, with minor halts, to the minimum in late September and early October.

Diaphanosoma appeared in traces in May but was not a regular constituent of the plankton until late June. The time of maximum abundance was early August when there were 6 per liter. During the remainder of the season the count was lower by one half or more.

Limnocalanus was present in the earliest samples and remained in small numbers through early July. It was most abundant in May, but never reached a count of 1 per liter. Epischura first appeared in early May and disappeared from the trap samples in early August. It was quite rare throughout its season, never becoming as abundant as 1 per liter. Bosmina appeared in late April at one station and attained some abundance throughout the section during May and June. It disappeared during July, but returned in August and remained for the balance of the season. The highest count recorded was 15 per liter at Station 59A in late June; the average for the section at this time was 4 per liter, and it was about equally abundant in early June. During the second period of abundance it was less abundant, and no counts of 1 per liter were recorded. Leptodora was present (always less than 1 per liter) from early May to end of the season.

The Rotifera were fairly abundant from April through June, but were rare during the rest of the season. There were marked fluctuations in abundance, with maxima indicated for early April, early May, and late June. After that time the counts were uniformly low.

Comparison of seasonal distribution in 1928, 1929, and 1930.

Fig. 21 was designed to facilitate comparison of seasonal distribution of the four leading crustacean groups in 1929 and 1930. Most of the following discussion will be devoted to those groups in the two years, although some attention will be given to other groups and to the data of 1928.

Diaptomus. Diaptomus was a much more important constituent of the plankton in 1929 than in 1930. For a large part of the period for which comparable data are available (May 16 - October 15) the counts for 1929 were well above those of 1930. The average abundance for this period was 9 per liter in 1929, and 4 per liter in 1930. It seems probable that there was no early season period of abundance in 1929, corresponding to the one found in May, 1930. The reason for believing so is that the water temperature in May, 1930 was almost two weeks in advance of the 1929 temperature (Fig. 8 and Fig. 9). Assuming that temperature is an important factor in the control of the increase of the crustacea, the increase for 1929 should come later than the one for 1930. The validity of this assumption is indicated by the fact that Cyclops, Daphnia, and the Nauplii were also more abundant in late May in 1930 than in 1929. It seems likely, then, that Diaptomus had only one period of abundance in the spring and summer of 1929 and this came in July, while it had two such periods in 1930, one in May, the other in late June. The seasonal distribution in 1928 was similar to that in 1930. There were two periods of abundance in each year and the times of these periods were not far different. However, the average abundance for the eight periods represented between late May and early October, 1928, was 8 per liter, which is twice that of 1930, and almost the same as that of 1929.

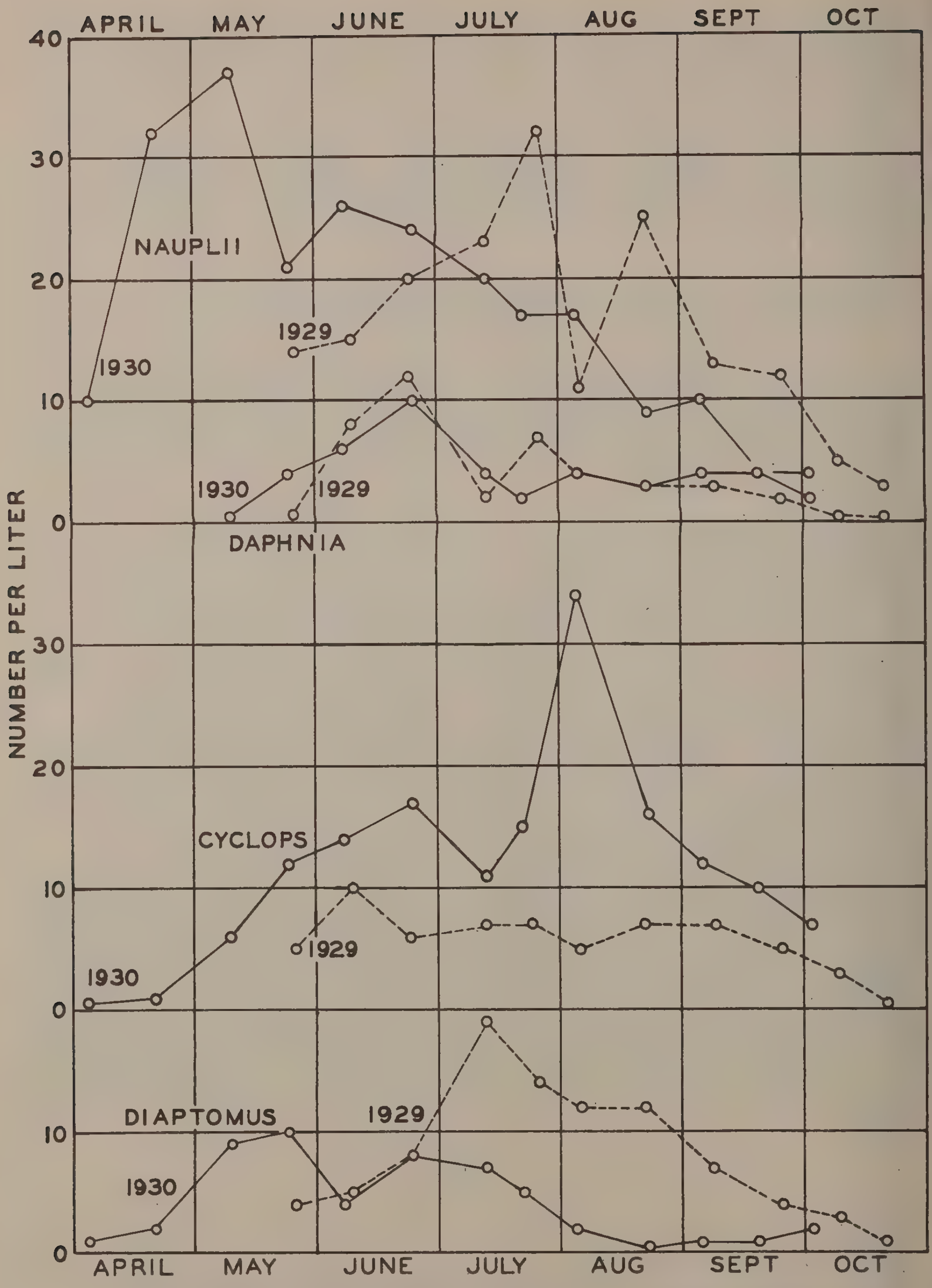

Fig. 21--Comparison of the seasonal distribution of crustacea in 1929 and 1930. Data taken from Tables 69 and 70.

Cyclops. Cyclops was much more abundant in 1930 than in 1929. At no time did the curve for 1929 cross the curve for 1930. The average number for the period May 16 to October 15 was 6 per liter in 1929 and 15 per liter in 1930. Not only was there a marked difference in abundance, but the times of abundance were different. In 1929 there was only one period of abundance (early May), and from late May until late September there was little change in abundance. In 1930 Cyclops began to increase earlier than in 1929, probably as a result of the higher water temperatures in 1930. There were two periods of abundance in 1930, and both came later than the one of 1929. There were also two periods of abundance in 1928, but the times of appearance were quite different. In 1928 they came in late May and early July rather than in late June and early August, as in 1930. The average number for the eight periods between late May and early October was 8 per liter, which is slightly more than that for 1929, and a little more than one half that of 1930.

Daphnia. Daphnia was equally abundant in 1929 and 1930. For the period May 16 to October 15 the average number was 4 per liter. It began to increase earlier in 1930 but at a slower rate, so that the maximum was reached at the same time. Following this, the decline was also slower in 1930, and the July minimum was reached somewhat later. The second increase for 1930 was not early as marked as in 1929 but its appearance in the same relative position suggests that it was real and not the result of inaccurate counting or inadequate sampling. The curves for the two years show remarkably close agreement, both in numbers present and in the times of abundance. Two periods of abundance were found in 1928 also, but they came at somewhat earlier dates. The average count was 5 per liter for the eight periods represented in the time between late May and early October.

Nauplii. The curves for the copepod nauplii in 1929 and 1930 are widely different. It has been pointed out before that there is some evidence that the nauplii were on the decline in late May of 1929, and it seems probable that if data were available, the curves would agree closely for the early spring period. The marked difference in abundance in the two years for late May and June probably resulted from the higher temperature of 1930. In 1930 the nauplii declined rather consistently from the high point of June, while in 1929 they increased during June and July, declined in early August, but increased again in late August. It seems probable that the discrepancies in the two curves resulted from the different start in development during June. The average number present during the period May 16 to October 15 was approximately the same in the two years; it was 17 per liter in 1929 and 15 per liter in 1930.

Rare forms. The distribution of Diaphanosoma was similar in the three years studied. It was somewhat more abundant in 1930 than in the other two years. It is essentially a summer form, with a maximum in July or August.

The remaining groups of crustacea were so rare in all years that comparison of the counts has little value. Limnocalanus was apparently more abundant and had a longer season in 1930 than in 1929, but was rare in both years. It is distinctly a cold-water form and is absent during the hottest period of the year. Epischura was present during all of the sampling season in 1929, but was not taken in trap samples after July, 1930. In 1928 it was present only occasionally. It rarely occurred at a station to the number of 1 per liter. Bosmina was about equally rare in all years. It had two periods of development, one in early summer, the other in late summer. Because of its small size and rarity, Bosmina probably has little importance in the plankton. Limnocalanus, Leptodora, and Epischura are rare also, but their large size gives them importance as food organisms.

Adequacy of the sampling program

The question of the adequacy of the sampling program may well be taken up at this point. Only the data for 1929 and 1930 will be used for purposes of illustration. It has been shown that the zooplankton is not uniformly distributed in the Island Section. In order to avoid inaccuracies arising from this condition, an attempt was made to sample several stations in each two-week period. In 1929, late July was represented by only three stations, early August by four, early October by one, and late October by two. The other periods were represented by seven or more stations. In 1930, the two periods in April were represented by two stations each, and the two periods in July by three stations each. The other periods were represented by five or six stations.

If this program of sampling were inadequate, we should expect the points on the curves for seasonal distribution to fluctuate up and down with no evidence of seasonal trends. Reference to Fig. 21 will show that each of the eight curves was low in spring and fall, and high at some time in the summer. Moreover, with minor exceptions, the fluctuations in abundance lack the appearance of being fortuitous. That is, in general, successive points show a progressive increase, decrease, or maintenance of abundance over a considerable period of time. The principal exception to this statement is seen in the curve for nauplii in July and August of 1929. The points of late July and early August were determined by the average of a few stations (3 and 4 respectively).

Whether the rapid change in abundance indicated was real or the results of inadequate sampling is open to question. The rapid change itself is not unquestionable evidence of inadequacy, for such changes in abundance are known to occur among the plankton crustacea. Too much importance should not be given to the fact that few stations were visited, because other periods represented by few stations yielded consistent results. For example, in July of 1930 each period was represented by only three stations, and yet the results for that month fit in well with the results taken before and after.

Additional evidence of adequacy is found in the close agreement in the numbers and times of abundance of Daphnia in the two years. It is extremely doubtful whether such close agreement is merely a coincidence. It is much more reasonable to suppose that the similarity in the curves resulted from a real similarlity in abundance and seasonal distribution.

The curves for Cyclops were quite different in the two years, and it seems highly probable that the difference was real. If the difference were the result of inadequate sampling, we should expect the curves to cross and re-cross in a fortuitous fashion. Actually the curve for 1929 is consistently low and does not cross the curve for 1930 at any point. A similar real difference is indicated by the results for Diaptomus.

In conclusion it may be said that the consistency and "reasonable" character of the results obtained leaves little doubt of their adequacy for the problem in hand. That is, it seems improbable that the conclusions reached in this paper would have been changed materially if a larger number of samples had been taken.

Abundance of zooplankton compared with that of other lakes

It is evident from the discussions of seasonal distribution that successive years may be quite different with regard to the abundance of crustacea and their times of development. The differences found in the three seasons studied emphasize the need in plankton investigations of continuous observations over several years. In Western Lake Erie there is a need especially for data on the zooplankton between the months of October and April. However, the available data make it possible to compare this lake with certain others for the period covered, and thus reached some conclusion as to the relative richness of the zooplankton per unit volume of water.

There are no data from the open waters of the Great Lakes which lend themselves to comparison with those reported here. However, Burkholder and Tressler (1932) obtained some results with a plankton trap in four bays at the east end of Lake Ontario. Three sets of samples were taken at each of six stations on the following dates in 1931: June 25, July 15 or 17, and August 17 or 19. Samples were taken at the surface and bottom, and the results are given in graphic form, divided into three groups: Copepoda, Cladocera, and Rotifera (their Figure 10). In Black River Bay, near the mouth of the river, the plankton was rare, but farther out at a depth of 16 meters, the mean counts for the three dates were: Copepoda (apparently including nauplii), 19 per liter; Cladocera, 3 per liter. In the Island Section of Lake Erie, for a corresponding period of time (late June - late August) of two years, the mean counts including the abundant genera only, were: Copepoda (including nauplii), 42 per liter; Cladocera, 7 per liter. The great abundance of crustacea in Lake Erie is offset to some extent by the rarity of rotifers: 7 per liter as compared with 36 in Black River Bay. Further, it should be noted that the figures for Black River Bay are based on surface and bottom samples only; the adult crustacea are usually most abundant at intermediate levels, so that the figures probably are too low. Two stations in Chaumont Bay (3 to 6 meters) yielded mean counts as follows: Copepoda, 31; Cladocera, 3; Rotifera, 73 per liter. Muskalonge Bay (2.5 meters) showed the greatest abundance of plankton: Copepoda, 42, Cladocera, 37, Rotifera, 72 per liter. Similar counts were recorded for a shallow station in Three Mile Bay, except for the Cladocera, which were rare. While these figures are somewhat unsatisfactory for purposes of comparison, principally because the nauplii are included with the adult copepods, it seems probable that the bays studied by Burkholder and Tressler are not excessively rich or poor in zooplankton as compared with the Island Section of Western Lake Erie.

More satisfactory comparisons can be made with three inland lakes of Wisconsin which have been studied in detail. The three lakes selected are Lake Mendota, studied by Birge (1898), and Green Lake and Lake Winnebago, studied by Marsh (1903). Lake Mendota is a rather shallow lake (25.6 meters) of the eutrophic type, while Green Lake is a deep lake (72.2 meters) of the oligotrophic type. Lake Winnebago resembles Western Lake Erie in having a great surface area (557.5 square kilometers) and meager depth (6.4 meters maximum).

Table 71 shows the two-year mean counts of Copepoda, nauplii, and Cladocera for the period from late May to early October, inclusive. Only the four most numerous genera of adult crustacea are included. For each lake the copepods include Diaptomus and Cyclops; the Cladocera include Daphnia and one other genus. In Lake Erie the second genus is Diaphanosoma; in Lake Mendota and Lake Winnebago it is Chydorus; and in Green Lake, Bosmina. The figures would be affected very little by the addition of the rarer forms, such as Epischura, Limnocalanus, and Leptodora. Both Birge and Marsh recorded their results in numbers per square meter of surface, and these have been changed to the number per liter by dividing by the depth of the sampling station in meters, and again by 1,000. For Lake Mendota this was 18 meters; for Lake Winnebago it was assumed to be 5 meters, and for Green Lake, 45 meters.

The data given in Table 71 need not be discussed in detail. It is evident that Lake Mendota had the highest mean number of crustacea (nauplii were not counted), and that Green Lake had the least. This finding is to be expected, for eutrophic lakes are, in general, much richer in plankton than oligotrophic lakes when they are compared on a per unit volume basis. The counts for the Island Section are lower than those for Mendota, but higher than those for Green, and, since Mendota and Green are fairly typical of their classes, it may be concluded that the Island Section stands between the plankton-rich and the plankton-poor lakes. In the absence of an exact measure of richness, it might be described as "moderately rich" in plankton crustacea. It is of considerable interest to note that the Island Section had counts closer to those of Winnebago, which it resembles hydrographically, than to those of the smaller and deeper lakes.

Portage River Section

Samples were taken from only one station in the Portage River Section. This was Station 159, located 1/4 mile straight out from the river's mouth. Conditions here are subject to marked changes due to the influence of littoral currents and intermittent discharge from the river itself. We should expect marked changes in the abundance of the various plankton organisms in such a situation, and a special investigation would be necessary to determine the effect of the numerous factors involved in the changes. The data collected here in 1929 and 1930 are shown in Table 72. It would be idle to attempt to discuss

Table 71.- Comparison of abundance of plankton crustacea in the Island Section of Western Lake Erie and in three Wisconsin lakes for the period May 16 to October 15. Abundance in individuals per liter

Lake	Years	Copepoda	Nauplii	Cladocera
Mendota	1895 - 1896	29	—	27
Green	1900 - 1901	5	3	1
Winnebago	1900 - 1901	8	9	6
Erie (Island Section)	1929 - 1930	16	16	5

seasonal trends, since the series of samples are too few in number. The crustacea were quite abundant as compared with the averages of stations in the Island Section, particularly in the year 1929 (see Tables 69 and 70).

Maumee Bay Section

In this section samples were taken at the three regular stations (250, 252, and 254). Sampling was started somewhat later here than in the Island Section and fewer samples were taken, so that data on seasonal distribution is much less complete. However, enough samples were taken to bring out some well defined differences between this section and others in the lake.

The results obtained from Station 250, located immediately outside the mouth of Maumee River, are shown in Table 73. Diaptomus was rare here in both years, while Cyclops was abundant in both years. It will be remembered that in the Island Section Diaptomus was the abundant form in 1929, and Cyclops in 1930. Another obvious difference is in the large number of nauplii at Station 250, especially in 1929. This is the only station in the lake which had more than 100 nauplii per liter at any time. The numbers of Daphnia fluctuated considerably, but the form was fairly abundant in both years. Diaphanosoma was rare in both years, except for the sample of September 7, 1929. The rotifers were very abundant in every sample taken in 1930. The principal ways in which this station differs from those in the Island Section are in the rarity of Diaptomus, and in the greater abundance of Cyclops, nauplii and rotifers.

The data for Stations 252 (Toledo Light) and 254 (Range Lights) are shown in Tables 74 and 75. To avoid undue repetition, we may omit separate discussion and pass on to a comparison of the data from the three stations (Table 76). In 1929, samples were not always taken at all three stations on the same date, hence comparisons are made between Stations 250 and 252, and between Stations 252 and 254. Samples were taken at Stations 250 and 252 within a short period of time on 5 dates. It will be noted that the differences between these two stations were of the same kind as between Station 250 and the Island Section. Diaptomus was much more abundant at the station four miles out in the bay than at the one near the river. Cyclops was less abundant, as were the nauplii. The Cladocera were somewhat more abundant.

Table 72.- Abundance of zooplankters at Station 159 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929							1930						
	June 21	July 11	July 22	July 30	Aug.20	Sept.9	Sept.24	May 13	June 17	July 6	July 26	Aug.4	Sept.2	Sept 16
Diaptomus	42	15	8	1	3	13	0	2	4	5	4	2	0	0.2
Cyclops	37	12	10	2	4	23	7	4	6	36	20	32	30	13
Nauplii	69	46	8	27	38	8	20	14	26	25	36	36	4	6
Daphnia	45	2	2	0	0.2	2	0.2	1	4	6	2	2	9	2
Diaphanosoma	5	5	4	1	0.5	10	0.2	0	0	3	2	6	3	2
Bosmina	6	2	2	0	1	0.2	2	0.1	0.3	1	3	3	2	14
Rotifera	--	--	--	--	--	--	--	7	5	72	22	5	2	2

Table 73.- Abundance of zooplankters at Station 250 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929						1930					
	June 26	July 17	Aug. 3	Aug. 23	Sept. 7	Oct.4	July 2	July 25	Aug. 14	Aug. 28	Sept. 9	Sept.29
Diaptomus	1	0.6	3	2	9	5	7	0.5	0.8	0	0.2	4
Cyclops	23	3	19	14	15	8	34	62	19	22	32	15
Nauplii	67	10	16	161	118	21	25	61	36	32	61	17
Daphnia	2	1	10	2	19	0.9	11	5	12	8	7	4
Diaphanosoma	0	0.5	1	1	10	1	2	1	0.8	0.2	2	0.2
Rotifera	—	—	—	—	—	—	71	52	128	116	157	82

Table 74.- Abundance of zooplankters at Station 252 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929						1930				
	June 26	July 17	Aug.3	Aug.23	Sept.7	Oct.15	July 25	Aug.14	Aug.28	Sept.9	Sept.29
Diaptomus	6	4	76	17	20	4	0	4	0.7	1	3
Cyclops	7	14	9	7	12	10	26	35	33	46	16
Nauplii	28	22	46	36	66	5	22	20	37	40	19
Daphnia	6	11	20	4	13	3	11	15	7	20	11
Diaphanosoma	2	2	11	4	11	0	2	2	0.2	1	0.8
Rotifera	—	--	—	--	—	—	50	12	51	124	114

Table 75.- Abundance of zooplankters at Station 254 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929				1930					
	July 17	Aug. 3	Sept. 7	Oct. 15	July 2	July 25	Aug. 14	Aug. 28	Sept. 9	Sept. 29
Diaptomus	33	19	9	4	9	2	1	1	0	1
Cyclops	2	3	6	8	29	23	19	33	28	3
Nauplii	62	18	2	6	25	8	10	17	12	2
Daphnia	16	22	2	2	18	7	3	6	11	1
Diaphanosoma	4	6	5	0.1	0.3	4	3	5	3	0.1
Rotifera	—	—	—	—	34	24	7	13	93	29

Table 76 .– Comparison of the abundance of zooplankters at stations in the Maumee Bay Section in 1929 and 1930. Abundance in individuals per liter. Data derived from Tables 73, 74, and 75

Plankter	Character of data, and stations compared						
	Average, five dates, 1929		Average, four dates, 1929		Average, five dates, 1930		
	250	252	252	254	250	252	254
Diaptomus	3	25	26	16	1	2	1
Cyclops	15	10	11	5	30	31	21
Nauplii	74	40	35	22	41	28	10
Daphnia	7	11	12	10	7	13	6
Diaphanosoma	2	6	6	4	0.8	1	3
Rotifera	--	--	--	--	107	70	33

Comparing the station at the range lights (252) with the one at the entrance to Toledo Harbor (254), we find a change in relationship. With increased distance Diaptomus decreased rather than increased in abundance. However, the decrease in Cyclops and nauplii continued. There was little difference in the numbers of Cladocera. The three stations can be compared more conveniently in the last three columns of Table 76, which show the average counts for five common dates in 1930. Diaptomus was so rare in 1930 that little reliance can be placed in the figures, but it is interesting to note that the highest average was recorded again for Station 252. Cyclops was equally abundant at the two inner stations but declined at the outer one. The nauplii showed a marked decrease as distance from the river increased, thus agreeing with the data of 1929. Daphnia was again most abundant at the middle station, Diaphanosoma was rare at all three stations, but showed a slight increase with increased distance from the river. The rotifers were very abundant near the river and dropped off markedly at the two outer stations.

The most striking feature of these data is the consistent and marked decrease in abundance of the nauplii and rotifers as one progresses from the river's mouth out into the lake. This finding is in accordance with expectation, for the plankton algae, upon which they feed in part, declined with greater distance from the river. In 1929 rotifers were not counted, but the nauplii decreased much as they did in 1930. The reason for the failure of the adult crustacea to decrease in the same way is not evident. The adults as a group were most abundant at Station 252 in both years, but there were notable exceptions among the individual genera.

In later pages the abundance of crustacea in this section of the lake will be compared with that of other sections.

River Raisin Section

Samples were taken only at Station 117 in the River Raisin Section. Five series were taken in 1929, and seven series in 1930 (Table 77). The data show clearly that Diaptomus was much more abundant in 1929 than in 1930, and that Cyclops was more abundant in 1930 than in 1929. Similar differences were noted in the Island Section. For comparable periods, the nauplii were about equally abundant in the two years, while Daphnia and Diaphanosoma were most abundant in 1930. The data of 1929 are too scattered to show any seasonal trends. In 1930, as far as comparisons can be made, the seasonal trends were similar to those in the Island Section for

Diaptomus, Daphnia, Diaphanosoma, and Rotifera. For Cyclops and the nauplii there was less agreement. The abundance of crustacea in this section as compared to that in the other sections will be considered in later pages.

Detroit River Section

Station 126 is located five miles out from the mouth of Detroit River, and the water here, except possibly under unusual conditions, has come directly from the river. Samples were taken at this station six times in 1929 and seven times in 1930 (Table 78). It is obvious from the results given that the water of Detroit River is extremely poor in plankton. None of the crustacean groups appeared in greater abundance than 3 per liter, and Daphnia appeared only in traces. The largest number of rotifers found was 5 per liter.

A possible explanation of the small amount of plankton here was suggested by the results obtained by Reighard in September, 1893. He found that the volume of plankton per unit volume of water near the islands of Lake Erie was three times the volume of plankton per unit volume of water in Lake St. Clair (Reighard, 1894, p. 37). Also, in the spring of the same year he found little plankton in upper Detroit River as compared with Lake Michigan (Reighard, 1893). Obviously if there were little plankton in the water entering Detroit River, there still would be little when it emptied into Lake Erie, for it is well known that plankton organisms do not reproduce well in rivers.

In order to get additional data on the plankton in Lake St. Clair, a trip was made to the lake on September 23, 1930, and samples were taken near Reighard's Station VIII. The depth was 3.9 meters. Trap samples were taken at depths of 0, 2, and 3 meters. The only form which had an average count of more than 1 per liter was Bosmina, with 4 per liter. Diaptomus, Cyclops, nauplii, and rotifers were each represented by 0.9 individual per liter, Daphnia by 0.1 per liter, and Diaphanosoma by 0.03 per liter. In view of such scarcity of plankton, we might expect the low counts recorded for Station 126 on the same date (Table 78). In addition to the forms shown in this table, Bosmina was found to the extent of 2 per liter. At this time there was still a considerable number of plankton organisms in the Island Section. On September 24 the following counts (per liter) were recorded for Station 8F: Diaptomus 0.5, Cyclops 10, nauplii 2, Daphnia 3, Diaphanosoma 0.5, rotifers 0.6. The average of several stations for the period September 16-30 was somewhat higher for most

Table 77.- Abundance of zooplankters at Station 117 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929					1930						
	July 16	Aug. 2	Aug.22	Sept.6	Oct.15	May 27	July 8	July 29	Aug. 7	Aug. 30	Sept. 12	Sept. 29
Diaptomus	19	13	4	16	0.1	3	2	2	2	1	0.8	0.8
Cyclops	4	7	2	8	0.3	8	36	13	25	15	16	8
Nauplii	18	41	38	6	2	21	22	31	11	49	4	2
Daphnia	5	11	2	0.3	0.1	5	17	9	12	3	3	2
Diaphanosoma	0.8	4	3	2	0	0	0	3	11	3	1	0.2
Rotifera	—	—	—	—	—	3	62	38	11	3	0.5	1

Table 78.- Abundance of zooplankters at Station 126 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929						1930						
	June 25	July 16	Aug.2	Aug.22	Sept.6	Oct.15	May 27	July 10	July 23	Aug.12	Aug.26	Sept.12	Sept.23
Diaptomus	0	2	3	0.9	2	0.6	2	0.5	0.2	0.1	0	0	0.5
Cyclops	0.5	0.2	1	0.6	0.9	0.1	1	0.5	1	2	3	1	0.1
Nauplii	1	1	2	2	3	0.7	3	2	2	0.7	1	0.1	0.2
Daphnia	0.1	0.4	0.2	0	0.2	0	0	0.1	0.2	0.6	0.8	0	0
Rotifera	--	--	--	--	--	--	0.7	5	4	2	2	3	0.7

Table 79 .- Abundance of zooplankters at Station 134 at various times during 1929 and 1930. Abundance in individuals per liter

Plankter	1929						1930				
	June 5	June 25	July 16	Aug. 2	Aug. 22	Oct. 15	July 8	July 30	Aug. 18	Sept. 4	Sept. 29
Diaptomus	2	3	6	7	0.3	0.1	0.6	1	0	0.2	0.4
Cyclops	2	0.9	3	2	0.3	0	0.6	8	2	4	8
Nauplii	6	13	14	27	6	0.3	2	10	5	1	6
Daphnia	0.4	11	3	5	0	0	0	0.2	1	0.2	2
Diaphanosoma	0	0	1	1	0	0	0	0.4	0.6	0.1	1
Rotifera	--	--	--	--	--	--	5	1	7	0.4	0.1

of these organisms (Table 70). All of our knowledge of the plankton of Lake St. Clair as compared with that of Lake Erie is derived from samples taken in September, and the apparent poverty of the plankton, relative to that of Western Lake Erie, may be due to an earlier decline in the upper lake. But since the low counts at Station 126 on September 23 were so obviously related to the low counts in Lake St. Clair, it is only reasonable to suppose that a similar relation existed for the consistently low counts recorded at Station 126 on other dates. That is, it is highly probable that Lake St. Clair is always poor in plankton, and consequently the river which drains it is always poor in plankton.

Although Station 134 is eight miles from Station 126, it is included with Station 126 in the Detroit River Section because it appears to be influenced strongly by the river. Samples were taken here on six dates in 1929 and on five dates in 1930 (Table 79). Comparison of the counts in this table with those in Tables 69 and 70 for the Island Section, Table 75 for Section 254, and Table 77 for Station 117, shows that Station 134 was relatively poor in plankton during both years. However, it had considerably higher counts than Station 126 for most of the samples taken on the same day or within a short period of time. The resemblance between counts at these two stations was closer than between Station 134 and any other station studied. This seems to indicate that Station 134 derives its water largely from Detroit River, as might be expected from the position of the station and the immense discharge of the river.

Comparison of abundance of zooplankton in different sections of Western Lake Erie

Study of the horizontal distribution of the crustacea in the Island Section of Western Lake Erie showed that the distribution was not uniform. However, there was no evidence that certain stations had consistently high counts and others consistently low counts. On the other hand, there is definite evidence of large and fairly consistent differences in abundance between different sections of the lake. Some of the more obvious differences have been noted, such as the rarity of organisms near the mouth of Detroit River, and the great abundance in Maumee Bay as compared with the Island Section. It seems advisable to make direct comparison of the sections at this time, in order to bring out the differences more clearly.

In presenting data on sections at the extreme west end of the lake, only those for 1929 and 1930 were included. The few data available

Table 80 .- Comparison of abundance of crustacea (except nauplii) in three sections of Western Lake Erie in 1928. Abundance in individuals per liter

Period	Section and station		
	Maumee Bay station 254	River Raisin station 118	Detroit River station 126
June 14 - 19	21	27	8
June 28 - July 2	26	24	4
August 20 - 28	43	58	0
October 19 -30	8	4	2
Mean	24	28	4

for the year 1928 are given in Table 80, which shows the abundance of adult crustacea (not nauplii) at one station in each of the three sections. Station 118 is located one mile north of Station 117. The data in Table 80 show that the crustacea were about equally abundant at Stations 254 and 118 during the four periods of time for which data are available. During the same periods, the abundance at Station 126 was only 1/6 of that at Station 254, and 1/7 of that at Station 118. It is not possible to make a satisfactory comparison of these stations with those in the Island Section, because the periods of time covered agree in only two cases.

The data obtained in 1929 and 1930 permit more adequate comparison. Table 81 was designed to facilitate such a comparison during five two-week periods in 1929. In this table both adult crustacea and nauplii are included. Station 250 is not included in the computations for Maumee Bay because conditions there are extremely variable, and the station is less representative of the general area than are Stations 252 and 254. Station 134 is excluded from the Detroit River Section in the interest of simplicity. For each period represented, the Maumee Bay Section had the highest counts, and the Detroit River Section had the lowest counts. Counts in the River Raisin Section were sometimes higher and sometimes lower than those in the Island Section; the mean count was slightly higher. In the Maumee Bay Section the mean abundance was 18 times that in the Detroit River Section, and nearly twice that of the other two sections.

Table 82 shows the same kind of comparison for 1930, except that in this case there are six consecutive two-week periods represented. Again the Detroit River Section had the lowest counts in each period represented. The River Raisin Section showed greater abundance than the Island Section in some periods, and less in others, and the mean again was greater. The Maumee Bay Section had the largest mean count of all the sections, but in certain of the two-week periods it had smaller counts than the River Raisin and Island Sections. If the abundance in the Detroit River Section be regarded as unity, the relative abundance in the other sections would be as follows: Maumee Bay, 20; River Raisin, 17; Island, 13. Thus, the different sections held the same relative positions with respect to abundance of crustacea in both years. The actual differences between means in the same sections in the two years are strikingly small in view of the short period of time involved. That is, the difference of 11 individuals in the mean count for the Maumee Bay Section, and the difference of 9 in the River Raisin Section, are not unexpectedly large.

Table 81 .- Comparison of abundance of plankton crustacea in different sections of Western Lake Erie, 1929. Abundance in individuals per liter. Data taken from Tables 74, 75, 77, 78, and 69.

Period	Section and stations			
	Maumee Bay, Stations 252 and 254	River Raisin, Station 117	Detroit River, Station 126	Island, Several stations
July 16 - 31	85	47	4	62
August 1 - 15	115	76	6	35
August 16 - 31	[1] 68	49	4	50
September 1 - 15	73	32	6	32
October 1 - 15	21	4	1	11
Mean	72	42	4	38

[1] Station 252 only

Table 82 .- Comparison of abundance of plankton crustacea in different sections of Western Lake Erie, 1930. Abundance in individuals per liter. Data taken from Tables 74, 75, 77, 78, and 70.

Period	Section and stations			
	Maumee Bay, Stations 252 and 254	River Raisin, Station 117	Detroit River, Station 126	Island, Several stations
July 1 - 15	[1] 81	77	3	43
July 16 - 31	52	58	3	40
August 1 - 15	56	61	3	63
August 16 - 31	70	71	5	32
September 1 - 15	81	25	1	29
September 16 - 30	28	13	0.8	20
Mean	61	51	3	38

[1] Station 254 only

Although the periods of time represented in Tables 81 and 82 are not exactly the same, there seems to be no serious objection to combining the means to obtain a two-year mean for each section. These means for nearly the same periods of the two years are (omitting decimals): Maumee Bay Section, 66 per liter; River Raisin Section, 46 per liter; Detroit River Section, 4 per liter; Island Section, 38 per liter. Now, if the mean abundance in the Detroit River Section be regarded as unity, the relative abundance in the other sections would be as follows: Maumee Bay, 16; River Raisin, 12; Island, 10. In other words there were 16 times as many crustacea in the Maumee Bay Section as in the Detroit River Section; in the River Raisin and Island Sections there were, respectively, 12 and 10 times as many as in the Detroit River Section.

In preparing Tables 81 and 82, data for Station 159, in the Portage River Section, were omitted because one or more of the two-week periods in each year were not represented at that station. The mean count in 1929 for four two-week periods which lie within the total period covered in Table 81 was 40 per liter (not including Bosmina). This figure agrees closely with those for the River Raisin and Island Sections in Table 81. In 1930 for five periods (early and late July, early August, early and late September) the mean count was 57 per liter. For the same periods the mean counts in the other sections were: Maumee Bay, 60; River Raisin, 47; Detroit River, 2; Island, 39. The probable significance of these comparative figures will be commented upon later.

The most striking fact brought out in Tables 81 and 82 is that the crustacea are very rare near the mouth of Detroit River, as compared with other parts of the lake. There may be a number of factors responsible for this marked inequality in horizontal distribution, but in all probability the factor of greatest importance is that of food. It is more than likely that the scarcity of crustacea in lower Detroit River is the direct result of a similar condition in Lake St. Clair. This condition in Lake St. Clair is believed to be the result of the small amount of food available to the crustacea. Samples taken on September 23, 1930 show that the phytoplankton, upon which the crustacea feed, was scanty as compared with the Island Section at about the same time. Poverty of phytoplankton in Lake St. Clair is indicated further by the studies of Reighard (1893 and 1894), and by the fact that Station 126, near the mouth of Detroit River, almost invariably yielded a small amount of phytoplankton.

In contrast to conditions at Station 126 we may cite the example shown by Stations 252 and 254 in the Maumee Bay Section. Here phytoplankton was extremely abundant; the mean abundance for a period of three months in 1930 was 26 times as great as at Station 126 (Table 62). Accompanying the great abundance of phytoplankton there was a great abundance of plankton crustacea; for the same period of time in 1930 the mean count was 20 times as great as at Station 126. Similar but less pronounced differences in both phytoplankton and zooplankton are evident in comparing the Detroit River Section with other sections of the lake.

The data of 1930 permit the demonstration of a still closer relationship between the abundance of the crustacea and the phytoplankton. For a period of three months, the sections, listed in descending order according to the abundance of both algae and crustacea, were: Maumee Bay, River Raisin, Island, and Detroit River (compare Tables 82 and 62). In view of this agreement, it is difficult to escape the conclusion that the marked inequalities in horizontal distribution of the crustacea are the result of the irregular distribution of the phytoplankton.

The relationship between the plants and animals probably is not entirely direct. Naumann (1918) found that fine organic detritus was a more important item of food for the crustacea than the living algae, but Klugh (1927) found the opposite to be true. The relationship between the abundance of phytoplankton and zooplankton, which has been observed many times, seems to be partly indirect, that is, through the organic detritus derived from disintegrating algal cells. In Western Lake Erie detritus derived from domestic sewage probably is an important part of the food of the crustacea, and probably, too, the relative positions of the different sections with respect to abundance of detrital food from sewage was the same as with respect to that derived from the algae.

It should be pointed out that the correlation between abundance of plants and of animals was not perfect. For example Maumee Bay had 26 times as much phytoplankton as the Detroit River Section, but only 20 times as many crustacea. In the Island Section there was four times as much phytoplankton, but 13 times as many crustacea, as in the Detroit River Section. The lack of perfect agreement is to be expected because the number of samples was not large enough to determine the mean abundance of plankton with great exactitude, and because sources of food for the crustacea other than the plankton algae and their products of disintegration tend to disturb the normal relationship. Station 159, in the Portage River Section, offers another example of lack of agreement. In the period of three months in 1930 the mean abundance of phytoplankton was 11 times as great as in the Detroit River Section, which would place the section somewhat below the River Raisin Section in order of abundance. Exactly comparable data are not available for the crustacea, but for five of the six two-week periods the mean abundance was 57 per liter, which was well above the mean abundance in the River Raisin Section for the same five periods. Thus this section held third place among the different sections in abundance of phytoplankton, but second in abundance of crustacea. Here, again, too few samples probably explain the discrepancy, for conditions are unusually changeable at Station 159.

In 1929 the sampling program was too irregular to allow a satisfactory comparison of the different sections with regard to the abundance of both phytoplankton and zooplankton. As far as comparisons can be made, they seem to confirm the broad conclusions reached from the data of 1930.

It was pointed out in the chapter on phytoplankton that the differences in abundance in the sections were in part the result of natural conditions, but that the differences have been accentuated by pollution. In view of the apparent relationship between the abundance of phytoplankton and crustacea, it is reasonable to suppose that there were differences in abundance of crustacea under natural conditions, and that these have been accentuated by pollution. That is, in all probability, the increase of phytoplankton and organic detritus resulting from pollution has made possible an increase of the crustacea.

The bottom organisms of the offshore waters of Western Lake Erie

Introduction

Previous investigations in the Great Lakes

Our knowledge of the bottom organisms of the Great Lakes is based almost entirely on qualitative studies. The first to use a dredge for this purpose was Stimpson (1870), who reported the kinds of animals taken in fairly deep water in Lake Michigan. Hoy (1872), who worked with Stimpson, also gave a brief account of the results. More extensive studies of the same kind were made by Smith (1871 and 1874) in Lake Superior, and by Nicholson (1872) in Lake Ontario. In addition to these general reports, there have been a number of reports on special groups of organisms. Such are certain of the appendices to a paper by Reighard (1894) on Lake St. Clair, and to a paper by Ward (1896) on

Lake Michigan in the Traverse Bay region. A number of groups have been studied qualitatively in Georgian Bay, for example the Ephemerida by Clemens (1915).

The Hirudinea and Oligochaeta of the Great Lakes region have been studied by Moore (1906); and a paper on the leeches of Ohio by Miller (1929) considers those found in Lake Erie. Meehean (1929) reported the presence of a marine annelid in Duluth Harbor, Lake Superior.

A number of papers on the Mollusca of the Great Lakes have appeared, and no attempt will be made to list all of them. The reader will find extensive literature lists in reports by Baker (1920 and 1928), Osborn (1930), and Goodrich and Vander Schalie (1932). Ahlstrom (1930) listed the molluscs found near the islands of Lake Erie.

For papers on other groups of organisms in Lake Erie the reader may refer to the bibliography compiled by Osborn (1930).

Almost nothing is known of the abundance of bottom organisms in the Great Lakes. Adamstone (1924) reported on a series of seven Ekman dredge samples taken in western Lake Ontario, and Sibley (1932) and Farrell (1932) reported some results obtained near the east end of the same lake. Cutler (1929) made a study of pollution along the shore at the east end of Lake Erie but did not report the number of organisms found. Osburn (1926 and 1926a) studied the question of pollution of the bottom in parts of Lake Erie, including the part covered in the present investigation. Unfortunately the animals in the dredge samples were not counted. The report consists of notes on the character of the bottom, and the kinds and general abundance of the included organisms. Consequently it is not possible to make detailed comparisons with the data taken in the present study. However, it may be said that, as far as comparisons can be made, the results obtained in the two investigations are in close agreement. Since the completion of this survey, Krecker and Lankaster (1933) published a report on the bottom fauna of the shores of Western Lake Erie.

Materials and methods

The present report is based on qualitative and quantitative samples taken in 1928, 1929, and 1930. For various reasons many of the quantative samples for all three years were not used. Of those taken in 1928, only 25 samples from 5 stations were incorporated in the report. The season of 1929 is represented by 196 samples taken at 14 stations, and 1930 by 215 samples taken at 91 stations. Qualitative hauls, made with a bottom sled (Helgoland trawl), numbered 24 in 1928 and 13 in 1929. Considering the large area covered, the number of samples taken was small, yet they suffice to show some well-defined characteristics of the bottom fauna, and justify certain conclusions with regard to abundance.

The work was done principally in the months of June, July, August, and September, although a few samples were taken earlier and a few later in the season. In 1929 and 1930 all of the sampling was done between June 15 and September 15.

In 1928 quantitative bottom samples were taken with an Ekman dredge 6 inches (15.24 centimeters) square. The dredge was identical in construction with the one described and pictured by Birge (1922). In 1929 this dredge was replaced by one which was 20 centimeters square. The large dredge could be handled almost as easily as the small one, and it took a much larger sample, the small dredge covering 232.25 square centimeters and the large one 400 square centimeters. The factors for converting the number of organisms per sample to the number per aquare meter were thus 43 and 25, respectively.

It is well known that the Ekman dredge works well only on a soft bottom, and for that reason it was replaced in 1930 by a Petersen dredge covering an area 27.3 by 27.0 centimeters or 737 square centimeters. The conversion factor was thus 13.5. After applying this factor, fractional numbers were rounded off to the nearest whole number. The Petersen dredge is so much more efficient than the Ekman dredge on sandy or gravelly bottom that its use is justified on such bottoms in spite of the inconvenience involved. It does not always take a quantitative sample; in fact at certain stations it was found impossible to take more than a small amount even after numerous attempts. The types of bottom which gave the greatest difficulty were those which contain stones large enough to become caught in the jaws and hold them open, and those with a substratum of hard clay.

In 1928 and part of 1929 the samples were washed through a series of two brass sieves having meshes of 1.0 millimeter and 0.5 millimeter. This method was found to be so laborious and time-consuming that it was abandoned for the more efficient method of washing through a dip net with a bag composed of No. 36 grit gauze. By the latter method a sample could be washed over the stern of the boat while it ran between stations. The entire operation consumed only a few minutes, compared with about one hour by the former method. In addition to the saving in time, the delicate bottom organisms suffered less mechanical injury in the net than in the metal sieves.

The bottom organisms were identified and enumerated in the laboratory. In all but a few cases, all of the organisms in a sample were counted, but at certain stations, such as Stations 200 and 250, the Tubificidae were taken in such large numbers that it was found desirable to count only a part of the residue of the washed sample and apply a factor to determine the total number. In such exceptional cases, care was taken to obtain a representative portion of the residue. This was done by adding water to the residue in a large beaker, mixing completely, and dipping up a sample before there was time for settling.

Because of the difficulty in getting samples on hard bottom and in getting the active organisms which live on or just above the bottom, the dredge hauls were supplemented by samples taken with a bottom sled (Helgoland trawl). The sled consisted of a sheet of heavy galvanized iron about 6 feet long and 3 feet wide, with a metal arch attached at the front end, to which was laced a bag of No. 0000 bolting cloth of the same shape as the sled. The front end of the metal sheet was turned up slightly to prevent the catching of snags. The sled was usually towed for a period of ten minutes at a speed of five miles per hour. The organisms taken were identified but not counted.

The reader will find considerable difference in the exactness of identification in different groups of organisms; some were identified to species while others were taken no further than the order. The policy in this regard was determined by expediency, that is, identifications were carried out as far as the available time, importance of the organisms, and knowledge of the staff members appeared to justify. Certain forms were submitted to experts for identification.

One group of organisms, the Nematoda, because of their small size and transparency, present a difficult problem in counting. At times they appeared in the samples in rather large numbers but it was found inadvisable to devote the time necessary to obtain accurate counts. For that reason, counts of nematodes have not been included in the tables of this paper. No attempt was made to study the numerous microscopic organisms which live on and in the bottom deposits.

Criteria of pollution

A study of the bottom deposits and the organisms living in or on them is essential in any investigation of the suitability of a body of water for fishes. The importance of the bottom and its associated organisms arises from two facts: first, that the eggs of most fresh-water fishes develop in contact with the bottom, and second, that the bottom organisms are used as food by a number of species of fishes. One of the essential needs of a developing fish egg is a constant supply of oxygen. If the bottom on which the developing egg lies contains a large amount of decaying organic matter, the available supply of oxygen will be usurped by the organic matter in the process of decay, and the egg will die. On such a bottom, too, there is danger of the egg's becoming covered with a layer of material which would tend to prevent ready interchange of gases. Since almost all of the commercial and game fishes of Western Lake Erie lay their eggs on the bottom, and many of them feed wholly or partially on bottom organisms, it follows that a study of the bottom and its associated organisms is of great importance in the present investigation.

The accumulation of masses of decaying organic matter on the bottom is one of the most striking results of pollution by domestic and certain types of industrial wastes. The amount of organic matter present can be determined by two methods: directly by physical and chemical analysis, or indirectly by a determination of the kinds and abundance of organisms living in the deposits. The first of these methods is somewhat outside the sphere of the biologists, and also requires time and special equipment. The second method lies within the field of the biologist, is less time-consuming, and calls for the same equipment used in the study of non-polluted bottoms. This method has been used in the present study and has been supplemented by general observations on the consistency, appearance, and odor of the bottom deposits.

The indirect method of study is based on the well-established fact that certain organisms thrive in the presence of an abundance of decaying organic debris, while certain others cannot exist in such a situation. It has been found that the number of certain tolerant organisms is roughly proportional to the amount of organic matter, while the number of certain intolerant organisms is inversely proportional to the amount of organic matter. These highly tolerant and highly intolerant forms are said to have index value, that is, they are good indicators of the degree of pollution. Certain other forms, while showing a distinct preference for polluted or non-polluted situations, have little or no index value because of their irregular occurrence.

A number of workers have developed systems of classification of bottom organisms on the basis of their tolerance to pollution. The classification which is most often quoted in this country and which has been found most useful in this study is the one developed by Stephen A. Forbes and his associates in their investigations of Illinois River. The most recent and complete presentation of the classification is found in a paper by Richardson (1928). Richardson was careful to point out the dangers involved in a rigid application of a set of rules in pollution studies.

In Western Lake Erie it was soon found that only two kinds of animals could be used as index organisms with any degree of confidence and one of these could be used only on mud bottom. A study of numerous samples from muddy bottom in the Island Section, far from sources of pollution, showed that the nymph of the burrowing mayfly, Hexagenia, was by far the most abundant organism, while tubificid worms of the genera Tubifex and Limnodrilus were found only occasionally, and never in large numbers. Samples taken at the mouth of Maumee River contained prodigious numbers of Tubificidae but no Hexagenia. Here there was a great deal of organic matter, but in the Island Section the mud was notably free from it. Samples taken 4 and 8 miles out from the river showed a progressive decrease in the organic matter and Tubificidae, and the appearance of Hexagenia. Similar experiences in other parts of the lake finally led to the adoption of these two kinds of organisms as the index organisms for those parts of the lake having a mud bottom. In this connection it is interesting to note that Richardson classified Tubifex and Limnodrilus as pollutional forms, and Hexagenia as a clean water form. Hexagenia prefers a soft mud bottom, and it finds conditions on hard bottom unsuited to its mode of life. For that reason it loses its index value on hard bottom, such as sand or hard clay. Tubificidae, however, thrive on a hard bottom provided there is a superimposed layer of decaying organic matter. The presence of large numbers of tubificids is not always an indication of sewage pollution. Populations of several thousand per square meter have been reported from the profundal region of Lake Mendota (Juday, 1922, p. 486); and of Third Sister Lake (Eggleton, 1931, p. 279). In these two cases the organic matter which supported the large populations was derived from natural sources.

The general plan of investigation, as suggested in the preceding paragraph, was to determine conditions in the lake far from the mouths of rivers, and then to compare them with conditions at the mouths of rivers where pollution would be suspected. This method was adequate to indicate the presence of pollution at the mouths of the rivers, but the regular stations were too few in number to permit determination of the extent of the polluted areas. In order to get sufficient data to make possible the attainment of this objective, a large number of special stations were established. These special stations were established along lines running from polluted stations toward the shore or toward points in the lake which were known not to be polluted. The distance between stations was determined largely by local conditions; in some area they were placed 1/4 mile apart and in others as much as two miles apart. All of the work of this kind was done in the summer of 1930, and because of the limitations imposed by the large area under investigation and the small amount of time available, fewer samples were taken than was desirable. However, it is believed that the limits of the polluted areas were determined with a fair degree of accuracy.

It was first necessary to devise an arbitrary measure of what constitutes pollution of the bottom deposits as determined by the kinds and abundance of organisms. From a study of many samples it was decided that, for mud bottom, less than 100 Tubificidae and more than 100 Hexagenia per square meter could be considered as indicative of clean conditions. More than 99 Tubificidae and less than 101 Hexagenia per square meter was considered to be indicative of a polluted bottom. It seemed desirable, also, to recognize different degrees or zones of pollution, such as light, moderate, and heavy pollution. These degrees or zones were arbitrarily determined on the basis of the number of Tubificidae as follows: light pollution, 100-999; moderate pollution, 1000-5000; heavy pollution, more than 5000 per square meter. It was found that in areas where the number of Tubificidae indicated heavy pollution, Hexagenia was usually entirely absent; but in the moderate and light zones the number of Hexagenia varied between 0 and 100, and did not show a close correlation with the number of Tubificidae. For that reason the number of Tubificidae alone was used in determining the limits between pollutional zones. A few stations on mud bottom showed very few of either of the two index organisms. In such cases, the number of Tubificidae was used as the criterion with regard to pollution.

On other than mud bottoms it was found, as previously stated, that Hexagenia had little or no index value, because even in the absence of organic debris it was rare or altogether wanting. The Tubificidae could be used as an index of pollution regardless of the substratum, because they appear to thrive wherever there is an accumulation of organic debris.

As an aid in the interpretation of results, a note regarding the type of bottom has been inserted in many of the tables of this paper. To conserve space, a system of symbols was used, as follows:

M = mud

S = sand

MS = principally mud, some sand

SM = principally sand, some mud

G = gravel

C = hard clay

R = bed rock or boulders

CS = hard clay overlain by sand

The meaning of other combinations of symbols will be obvious to the reader.

Acknowledgments

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Data and discussion

Qualitative data

Organisms taken in quantitative dredges

Nematoda

1. Nematoda.

Oligochaeta

2. Tubifex sp.

3. Limnodrilus sp.

Hirudinea

4. Herpobdella punctata (Leidy)

5. Dina fervida (Verrill)

6. Glossiphonia stagnalis (Linnaeus)

7. Glossiphonia fusca Castle

8. Glossiphonia nepheloidea (Graf)

Crustacea

Gammarus sp.

Hyalella knickerbockeri (Bate)

Cambarus propinquus Girard

Insecta

Hexagenia (see Neave, 1932)

Trichoptera

Chironomidae

Gastropoda

Helisoma trivolvis (Say)

Physa sayii (Tappan)

Physa sp.

Campeloma decisum (Say)

Valvata tricarinata (Say)

Bithynea tentaculata (Linnaeus)

Amnicola limosa parva (Lea)

Somatogyrus subglobosus (Say)

Pleurocera acuta Rafinesque

Goniobasis livescens Menke

Lamellibranchiata

Fusconaia flava parvula Grier

Elliptio dilatatus sterkii Grier

Strophitus rugosus (Swainson)

Anodonta grandis Say

Proptera alata (Say)

Leptodea fragilis (Rafinesque)

31. *Obovaria leibii* (Lea)
32. *Eurynia nasuta* (Say)
33. *Lampsilis siliquoidea rosacea* (DeKay)
34. *Lampsilis ventricosa canadensis* (Lea)
35. *Truncilla truncilla* Rafinesque
36. *Truncilla donaciformis* (Lea)
37. *Sphaerium solidulum* Prime
38. Musculium transversum (Say)
39. *Pisidium compressum* Prime
40. *Pisidium scutellatum* Sterki
41. *Pisidium concinnulum* Sterki

Organisms taken in bottom sled

Hauls of the bottom sled or Helgoland trawl in the Island Section revealed the presence of some organisms which never appeared in the quantitative dredges. Some of them were active swimmers which live on or just above the bottom, while others were rare forms which might be missed by samples covering only a small area. The form which appeared most frequently in large numbers was the insect, Corixa. Other insects which appeared only in the bottom sled were larvae of the stonefly, Perla; and larvae of the mayflies, Heptagenia, Ephemera, Ephoron, and Baetisca. Beetle larvae and dipterous pupae of unknown affinities were also taken. The crustacean, *Mysis oculata relicta* Lovén, was taken on several occasions. This form was also present in the plankton. The following lamellibranchs appeared only in the bottom sled collections: *Obliquaria reflexa* (Rafinesque), *Ligumia recta* (Lamarck), and *Amblema costata plicata* (Say). In addition there were occasional specimens of a mite (Eylais), an annelid (Sparganophilus), and a crustacean (Leptodora). All organisms taken in the quantitative dredges were taken also in the bottom sled.

Many of the hauls were made on firm bottom offshore. There was no evidence that areas which had formerly had a bottom of sand, gravel, or boulders had been covered by deposits of silt or organic debris. It will be shown later, also, that there was no evidence of pollution in the relatively deeper areas with a mud bottom.

Quantitative data

Island Section

Abundance of bottom organisms

In the summer of 1928, work on bottom organisms was necessarily subordinate to the fisheries investigation. As a result, the total number of samples taken was small, and most of the stations are represented only by single samples. While the data obtained were valuable in making plans for the more detailed investigations of 1929 and 1930, those from the Island Section are considered too incomplete to be introduced here.

In 1929 the number of stations was reduced, but they were visited at more regular intervals and more samples were taken, so that the data may be considered more representative. In the Island Section eight stations were established. Seven of these stations had a soft mud bottom in which the Ekman dredge worked well, but at the remaining one (Station 18, Pelee Island) the bottom was stony and it was impossible to take samples. Hence, the quantitative data for the Island Section covers only the areas with a mud bottom.

It is customary, at the present time, to divide lakes into three zones with regard to benthic habitats: Littoral, sub-littoral, and profundal. The profundal zone is, of course, not present in Western Lake Erie. The dividing line between the littoral and sub-littoral zones is usually placed at the depth where rooted vegetation ceases to grow, but in Western Lake Erie the shores are so exposed to wave action that rooted vegetation is almost entirely lacking, and this criterion must be abandoned. Without attempting to define the limits of the two zones, it may be stated confidently that all of the stations studied in the Island Section lie within the sub-littoral zone. The results obtained at the seven stations studied in 1929 are shown in Table 83. The table shows, for each station, the number of samples taken, the mean number of organisms per square meter, and the mean number for the seven stations. Certain organisms which were very rare are not included in the table. It should be remembered that the dredge covered an area of 400 square centimeters and that in converting the number per sample to the number per square meter the factor 25 was used. Because of this large conversion factor, too much importance should not be attached to small differences in the numbers of organisms at the various stations.

Reference to Table 83 shows that the nymphs of the burrowing mayfly, Hexagenia, were far more abundant than any other kind of organism. At six of the seven stations the number exceeded 200 per square meter, and at Station 37A (Kellys Island) reached the high number of 508. At Station 75 (West Sister Island) there were only 43 per square meter. The reason for their comparative rarity at this station is not known, but obviously it was not pollution, for tubificid worms were rare also. It may be seen that the mean number of 283 per square meter for all seven stations was about five times as great as the number of the next most abundant group, the Chironomidae. The remaining groups were rather rare at most of the stations and none reached a mean number of 25 per square meter, or one per haul of the dredge. The tubificid worms ranged in number from 2 to 22 per square meter, and the mean for the seven stations was twelve.

In 1930 samples were taken at only five stations; Station 82 was abandoned and Station 72 was substituted for Stations 68 and 75. Fewer samples were taken also: 43 in 1930 as compared with 121 in 1929. It should be remembered, however, that the dredge used in 1930 covered almost twice the area of the one used in 1929, so that the difference in area dredged was much less than the difference in number of samples indicates.

The data in Table 84 show that in 1930 Hexagenia was much more abundant than in 1929. Of the four stations studied in both years, only one (Station 37A) showed a lower count for 1930, and the difference was small compared with the increase at the other stations. If we assume that the data collected at the four stations were representative of conditions in the two years, we may say that Hexagenia was about one and one-half times as abundant on mud bottom in 1930 as in 1929. The mean number for the two seasons (all stations) was 396 per square meter.

All of the other groups of organisms were less abundant in 1930 than in 1929 except the snail, Amnicola. The mean number of organisms other than Hexagenia for all stations was 153 per square meter in 1929 and only 77 per square meter in 1930. Thus, there was a marked increase in the numbers of Hexagenia relative to the other organisms. In 1929 Hexagenia made up 65 per cent of the total number of organisms, while in 1930 it made up 87 per cent of the total.

These percentages are probably much lower than they would have been had the sampling been carried on over the entire year. Most of the sampling was done following the emergence of tremendous numbers of Hexagenia in late June and early July. The effect of this emergence is

Table 83 .- Number of bottom organisms per square meter at seven stations in the Island Section, 1929

Item	Station							Mean
	8F	37A	59A	82	158	68	75	
No. of samples	18	18	23	14	20	17	11	---
Hirudinea	9	43	6	41	6	38	22	24
Tubificidae	12	22	16	7	6	20	2	12
Hexagenia	248	508	323	230	312	317	43	283
Trichoptera	3	19	16	9	20	20	36	18
Chironomidae	41	90	66	32	81	28	51	56
Valvata	1	3	1	19	6	26	9	9
Amnicola	7	1	8	27	6	1	25	11
Sphaerium	8	4	2	0	4	10	70	14
Musculium	1	0	0	7	6	1	2	2
Pisidium	1	3	12	3	6	9	16	7

Table 84 .- Number of bottom organisms per square meter at five stations in Island Section, 1930

Item	Station					Mean
	8F	37A	59A	158	72	
Number of samples	6	7	5	16	9	--
Hirudinea	2	3	[1]50	4	9	14
Tubificidae	7	3	10	3	4	5
Hexagenia	565	458	692	505	328	510
Trichoptera	0	3	0	1	0	1
Chironomidae	12	34	36	22	1	21
Valvata	0	1	0	3	0	1
Amnicola	0	3	78	21	5	21
Sphaerium	7	1	17	1	14	8
Musculium	0	0	4	3	0	1
Pisidium	2	0	17	4	2	5

[1] Mostly juvenile

well shown in Table 85. At each station the mayfly larvae were more abundant in late June than at any later time. In fact the reduction between late June and early August was on the average, nearly 50 per cent. In all probability, then, if samples had been taken throughout the year of 1930, or if as many samples had been taken before as after emergence, the Hexagenia count would have made up well over 90 per cent of the total count of bottom organisms.

The explanation for the greater abundance of Hexagenia in 1930 than in 1929 is not known, but there is no reason to doubt that the difference in the two seasons was real rather than the result of inadequate or improper sampling. It is highly improbable that the abundance was the same in the two years, and that the times of sampling in relation to emergence of the insects was responsible for an apparent difference in abundance. If the samples of 1930 had been taken earlier in the season than those of 1929 (that is, principally before emergence in 1930, and principally after in 1929), the observed difference would be expected. But in both years the sampling period was the same (June 15-September 15), and successive samplings were quite uniformly distributed through the season. A second reason for believing that emergence was not involved is that the season of 1930 was earlier than 1929 with respect to temperature, and emergence should have taken place earlier in the warmer season. If emergence did take place unusually early in 1930, we should expect lower average counts in that year than in 1929. The fact that the opposite was found, strongly suggests that Hexagenia was actually more abundant in 1930 than in 1929.

It is evident from the large number of Hexagenia nymphs and small number of tubificid worms that the bottom was not polluted.

A review of the literature on North American lakes shows that Western Lake Erie occupies a unique position by virtue of the overwhelming abundance of Hexagenia in its bottom fauna. Lake Winnepeg is the only other lake which has come to the attention of the writer that even approaches Western Lake Erie in this respect. Neave (1932) studied the two species of Hexagenia in this lake, and found them abundant, although he did not state their abundance relative to other forms. Samples taken before the annual emergence showed an average of 68 per square meter in the southern part (average depth, 12 meters) and 137 per square meter near the Narrows. These figures may be compared with an average of 283 (in 1929), and 510 (in 1930) in Western Lake Erie, based on samples taken principally after emergence. It

Table 85.– Abundance of Hexagenia larvae at five stations in the Island Section at various times during the summer of 1930. Abundance is stated in individuals per square meter

Time of sampling	Station				
	8F	37A	59A	158	72
Late June	1040	688	1161	533	412
Early August	371	284	634	496	280
Late August	432	—	364	472	—
Early September	418	203	608	412	310

would be of interest to have figures from the two lakes over comparable periods of time, but it is obvious that the density of population is much greater in Lake Erie.

In their brief study of Lake Michigan, Stimpson (1870) and Hoy (1872) found no mayfly larvae. Smith (1871 and 1874) reported only a single specimen from the bottom of Lake Superior, and noted the relative scarcity of cast skins as compared with the lower lakes. Nicholson (1872) found the mayfly larvae rare and confined to shallow water in Lake Ontario. In a small group of samples taken in the same lake in 1922, Adamstone (1924) found no mayflies. Clemens (1915) made a study of the mayflies of a small area in Georgian Bay, Lake Huron, but gave no data on their abundance relative to other groups.

In Lake Nipigon, according to Adamstone (1924), the Ephemerida were less abundant than five other groups of animals. Hexagenia was the most abundant mayfly and it reached its greatest concentration (34 per square meter) where the water was less than two meters deep. Muttkowski (1918), in his study of the littoral bottom fauna in Lake Mendota, found the mayflies less abundant than the Trichoptera and Chironomidae, and certain groups other than insects. Hexagenia was not recorded for this lake. Baker (1918), working in Lower South Bay, Oneida Lake, in July, found the mayfly larvae rather rare at that time, but enormous flights of adults had been reported for June. Baker stated that Hexagenia nymphs descended to a depth of about 15 feet (4.5 meters). Three of the Finger Lakes studied by Birge and Juday (1921) had few if any Ephemerida at the depths investigated, although the depths were greater than mayflies usually select. Juday (1922) reported no mayflies in five samples taken in the deeper water (20 meters or more) of Lake George. Ephemerida made up only a small part of the bottom fauna of Green Lake, Wisconsin, even in the littoral zone, where they were found in the largest numbers (Juday, 1924). According to Scott, Hile, and Spieth (1928), mayflies in the littoral zone of Lake Wawasee, Indiana, were rather abundant, but less so than Amphipoda and Chironomus. Rawson (1930) found the Chironomidae by far the most abundant group in Lake Simcoe, with the Ephemerida fifth in order of abundance. The mayflies as a group were most abundant where the water was less than five meters deep, but Hexagenia was most abundant at 15 meters. Eggleton (1931, page 259) found only occasional Ephemerida in his study of Douglas Lake and Third Sister Lake, Michigan, and Kirkville Green Lake, New York.

All of the lakes which have been discussed in the preceding two paragraphs are quite different from Western Lake Erie in their hydrographic features, and it is not surprising that they should differ from it in the make up of their bottom faunas. However, there is no better agreement in the case of Lake Winnebago, which is similar to Western Lake Erie in its large surface area and meager depth. Here, also, the mayflies occupy a subordinate position relative to a number of other groups (Baker, 1924).

Weight of Organisms

Since the data on bottom organisms in the Island Section were all taken from stations on mud bottom, they form an imperfect basis for the determination of abundance for the Island Section as a unit. But so large a part of the Island Section has a mud bottom that it seemed worth while to make an approximate determination of the weight per unit area of the standing crop in summer. It was possible to make determinations of the weight of Hexagenia only. Four groups of 25 individuals, selected at random, were dried at 65°C. for a period of 24 hours, weighed, then ignited in an electric furnace, and weighed again. The mean dry weight of an individual Hexagenia larva was found to be 10.9 milligrams, and the mean weight of organic matter, as indicated by the loss on ignition, to be 8.6 milligrams.

If we apply these figures to the mean number of Hexagenia at the seven stations in 1929, we find that the dry weight of the crop was 30.8 kilograms per hectare (27.5 pounds per acre), and the weight of organic matter 24.3 kilograms per hectare (21.7 pounds per acre). For 1930, the dry weight of the Hexagenia crop was 55.6 kilograms per hectare (49.6 pounds per acre), and the weight of organic matter 43.8 kilograms per hectare (39.1 pounds per acre). From the results obtained by other workers, it has been estimated that the addition of the dry weight of the associated organisms would increase the 1929 crop about 2 kilograms per hectare, and the 1930 crop about one-half that amount. The average weight of Hexagenia for both 1929 and 1930 is as follows: dry weight, 43.2 kilograms per hectare (38.5 pounds per acre), and weight of organic matter, 34.1 kilograms per hectare (30.4 pounds per acre).

It is recognized that the foregoing figures represent the sub-littoral zone only imperfectly. But, admitting the deficiencies in the data, it seems worth while to compare them with data from similar zones in certain other lakes. To facilitate the comparison, Table 86 was assembled, showing, besides the dry weight of Hexagenia per unit of area in the area under consideration, the dry weight per unit of area for all organisms in parts of Lakes Wawasee, Mendota, Green, Simcoe, and Nipigon. An attempt was made to select data from a zone in each lake as much as possible like the sub-littoral of Western Lake Erie. In Lake Wawasee, and to a lesser extent in Lake Mendota, the lower parts of the zones selected lie below the thermocline, and are subject to oxygen depletion during the summer. The zones selected in the other lakes lie entirely within a region of high oxygen content, and thus have conditions more like those in Western Lake Erie.

In Table 86 the lakes are listed in order according to the weight of organisms per unit of area, with Wawasee first, Mendota second, Western Lake Erie third, and Green, Simcoe, and Nipigon following in the order named. Lake Wawasee supports by far the largest crop of bottom organisms. Lake Mendota and the Island Section of Western Lake Erie are nearly the same in this respect, but it is almost certain that, if records from the latter were available for an entire year, it would hold second place in the list. Green, Simcoe, and Nipigon, particularly the last two, are relatively poor lakes. It is evident from the figures given that the Island Section of Western Lake Erie compares favorably with North American inland lakes with respect to the weight of bottom organisms per unit of area.

Portage River Section

Samples were taken at only one station in this section. This was Station 159, located one-fourth mile north of the mouth of the river. The bottom is composed of sand with a slight admixture of mud. Fourteen samples were taken here in 1929, and seven in 1930. Very few organisms were found at any time. In 1929 there was an average of 19 tubificid worms and 18 chironomids per square meter. No Hexagenia were found in 1929, but a few specimens were obtained on a single date in 1930. Their rarity is readily explained by the fact that the bottom material is almost wholly sand. Tubificids did not appear in the samples of 1930. It seems probable that waves and currents tend to prevent the deposition of any organic debris which may be discharged from the river. At least there was very little of such material on the bottom, and the biological data give no evidence of pollution.

Maumee Bay Section

Regular Stations

In the Maumee Bay Section there are a number of special conditions which determine the type of organisms to be found in the bottom deposits. Maumee Bay itself is somewhat enclosed, and is protected

Table 86.- Comparison of the dry weight of Hexagenia on mud bottom in the Island Section of Western Lake Erie, with the dry weight of all organisms in the most nearly comparable zone of five other lakes

Lake	Authority	Depth range, meters	Kilograms per hectare	Pounds per acre
Wawasee	Scott et al., 1928	4 - 23	[1]76.2	68.0
Mendota	Juday, 1922	8 - 20	48.2	42.9
Western Lake Erie	This report	7 - 14	43.2	38.5
Green	Juday, 1924	10 - 20	29.9	26.7
Simcoe	Rawson, 1930	5 - 14	8.2	7.3
Nipigon	Adamstone, 1924	9 - 18	2.3	2.0

[1] Calculated from the wet weight which included mollusc shells. It was assumed that the shells made up 70 per cent of the total mollusc weight, and that the dry weight of all organisms was 15 per cent of the wet weight.

from the wind except when it blows from the northeast. The bay is very shallow except for the narrow ship channel, which has a depth of 6.4 meters. The current of Maumee River is subject to periodic reversals and is never very strong during the summer period of small discharge, but the water is extremely turbid and carries a large amount of organic debris. A large part of the organic debris is deposited near the mouth of the river, but apparently the ship channel tends to operate as an extension of the river channel for a distance of about nine miles. That is, there is a tendency for the river water and some of its organic debris to be retained within the channel and thus to be carried much farther from the mouth of the river than if the channel were not there.

Three regular stations were established along the ship channel and were studied in 1929 and 1930. Two of them were sampled also in 1928. Station 250 is located at the red buoy just out of the river's mouth, where the depth in 1929 was 3 meters. Early in 1930, dredging operations for the improvement of the harbor increased the depth to about 6.4 meters, except for a very small area close to the buoy. Station 252 is located at the range lights, a little more than 4 miles from Station 250. Bottom samples were taken on either side of the crib, depending on which gave the greater protection from the wind. The depth here is 4 meters at a distance of about 3 meters from the crib. Station 254 is located on the east side of the channel, opposite Toledo Harbor Light, where the depth is 6.2 meters. This station is 4 miles from Station 252.

In 1929 the bottom at Station 250 consisted of fine silt which contained a large amount of organic matter in all stages of decomposition. Most of the bottom material was in a finely divided state but contained, also, a large number of vegetable fibers which would not pass through the meshes of the sieves or net. Its odor was similar to that of sludge, with the addition of a distinct oily odor. The oily matter could be seen readily when the sample was mixed with water; the surface would be covered immediately with a film of oil. In 1930, in the course of dredging operations, much of the accumulated organic debris was removed from Station 250 and deposited some distance west of the channel. As a result there was a noticeable improvement in the appearance and odor of the bottom samples. The bottom at Stations 252 and 254 contained much less organic debris and oily matter than at Station 250, even after the marked improvement at the latter. At the two stations farther from the river, there was some sand present.

The data on bottom organisms collected at these three stations are shown in Table 87. The outstanding feature at Station 250 was the presence of large numbers of tubificid worms, especially in 1929. The reduction in average number from 383,500 per square meter in 1929 to only 15,470 in 1930 is readily explained by the changes in the bottom noted above. There was also a notable decrease in the number of Musculium transversum, a sphaeriid regarded by Richardson (1928) as unusually tolerant to pollution. The many young Sphaeriidae, which were not identified to genera in 1930, were probably Musculium, as in 1929. The chironomidae showed an increase in 1930 over 1929, but since the identifications were not carried beyond the family group, the significance with regard to pollution is open to question. A slight indication of better conditions in 1930 is seen in the appearance of small numbers of Sphaerium, and Bithynia, both of which are regarded as being much less tolerant to pollution than Musculium transversum. Hexagenia nymphs were not found in either year, nor were the molluscs, Valvata, Amnicola, and Pisidium.

This station must be regarded as heavily polluted. Examination of the bottom deposits shows the presence of a large amount of decaying organic matter, and the most abundant organisms are tubificid worms and Musculium transversum, which are rare in the open lake and are known to thrive in polluted areas. The case is strengthened by the total absence of Hexagenia, a clean-water form which is characteristic of the open water, far from sources of pollution. The apparent improvement noted in 1930 was not a real improvement at all, because the objectionable deposits were merely transferred from one place to another.

No attempt was made to weigh the organisms taken at Station 250. However, in view of the tremendous numbers of Tubificidae observed there in 1929, it may be of interest to estimate their weight per unit area. Juday (1922, p. 486) found the average dry weight of an individual tubificid to be 0.3119 milligram. If the tubificids at Station 250 had the same average weight, the dry weight of these forms alone was 1,196 kilograms per hectare (1,067 pounds per acre) in 1929. This figure is roughly 39 times as great as the corresponding figure for Hexagenia in the Island Section for the same year. It is evident that the heavily polluted bottom supported a much larger crop of living organisms than the clean bottom of the open lake.

Wiebe (1928, p. 148) reported one station in the upper part of Mississippi River which had a somewhat denser population of tubificids than Station 250 in 1929. The station was within the city limits of Minneapolis and yielded 364,000 worms per square yard, or 347,000 per square meter. Wiebe found a number of points where there were several

Table 87 .- Number of organisms per square meter at the three regular stations in the Maumee Bay Section, 1929 and 1930

Item	Station					
	250		252		254	
Year	1929	1930	1929	1930	1929	1930
Number of samples	10	6	8	6	8	6
Hirudinea	7	16	115	441	59	76
Tubificidae	383,500	15,470	1,165	1,040	31	504
Hexagenia	0	0	9	37	22	63
Trichoptera	2	0	6	8	72	0
Chironomidae	50	146	53	92	156	98
Bithynia	0	11	3	130	31	5
Valvata	0	0	3	11	106	16
Amnicola	0	0	0	289	50	14
Sphaerium	0	5	0	24	3	11
Musculium	6,900	368	9	27	175	35
Pisidium	0	0	0	116	109	16
Sphaeriidae (juvenile)	—	3,660	—	794	—	270

thousands per square yard. None of the reaches of Illinois River from LaSalle to Beardstown had an average count of tubificids as high as Station 250 (Richardson, 1928). However, LaSalle is about 100 miles below the principal source of pollution (Chicago), and it is probable that parts of the river above LaSalle would show much higher counts than those below (see Forbes and Richardson, 1913).

At Station 252 there was marked improvement over the station nearer the mouth of the river. All of the groups of organisms listed in the table were found in at least one of the two years, while at Station 250, four groups were absent in both years. More striking evidence of improvement is seen in the great reduction in numbers of tubificid worms and Musculium, and the appearance of Hexagenia. Comparing the two years at Station 252 we find that the number of tubificids remained almost unchanged, but Hexagenia and Musculium increased. These and other differences, such as the increase in numbers of Hirudinea, Chironomidae, and Amnicola, are considered to be of no significance as indicators of changes in the degree of pollution. According to the number of tubificid worms, this station belongs to the zone of moderate pollution. The single sample taken in 1928 showed 6,320 tubificids per square meter, but no Hexagenia.

The data for Station 254 are rather contradictory in that both tubificids and Hexagenia increased in 1930 over 1929, while most of the associated forms decreased. In the season of 1928, 10 samples were taken at this station on four dates. The mean number of Hexagenia was 38 per square meter, and of Tubificidae, 163 per square meter. These results fall between those of 1929 and 1930. Differences in the data of the three years are probably best explained by the existence of marked inequalities in distribution. That the distribution is not uniform is shown by the fact that, in the various samples taken in 1930 the number of Tubificidae ranged from 7 to 1,930 per square meter, and Hexagenia from 27 to 168 per square meter. It is probable that the channel was the most important factor in determining such large differences in samples taken within a small area. It will be shown later that organic debris tends to be confined within the channel, and we should expect a marked falling off in pollution with increased distance from the channel. It is, of course, impossible to take successive samples at exactly the same point, and differences in position relative to the channel would be reflected in differences in the character of the fauna. Averages of the index organisms for the three years place this station in the zone of light pollution.

The data show that the bottom was polluted at all of the regular stations in the Maumee Bay Section. In order, then, to determine more definitely the extent of the polluted area, samples were taken at numerous special stations along lines radiating from the outermost regular station (254), and at other points of special interest. Some of these special stations were sampled in 1928 also. The data collected will be discussed in the two following sections.

Extent of pollution out from the mouth of Maumee River

Table 88 shows the abundance of Tubificidae and Hexagenia at 12 stations located on a straight line between Station 250, at the mouth of the river, and Station 134, approximately twenty miles out in the lake. In addition to the three regular stations of the Maumee Bay Section, and Station 134, eight special stations are shown. The locations of these special stations with reference to Station 250 are given in the table, and in Figure 22 and Figure 23. All of the stations in this series had predominatly mud bottom.

Station 251, situated about equidistant from Stations 250 and 252, had almost as many Tubificidae as Station 250, but about 11 times as many as Station 252. It will be remembered that dredging operations were carried out at Station 250 before these samples were taken, and as a result the number of Tubificidae in 1930 was much less than in 1929. Had it not been for this dredging, the data of 1930 undoubtedly would have shown a greater dropping off of Tubificidae between Stations 250 and 251 than between Stations 251 and 252. Regardless of this point, it is obvious that the dividing line between the zones of heavy and moderate pollution should be placed between Stations 251 and 252. Between Stations 252 and 253 there was a decrease of several hundred worms per square meter, and a change from moderate to light pollution. In passing from Station 253 to Station 254 we note an increase in the Tubificidae, probably as a result of the "spotty" distribution of the organisms. Both stations belong in the zone of light pollution.

At Station 255, only one mile out from Station 254, the single sample showed a total absence of Tubificidae, and the presence of more than 100 Hexagenia per square meter. There may be some hesitation in relying on the results of a single sample, but certainly the results at Station 256, one mile farther out, indicate conditions typical of unpolluted bottom such as was found in the Island Section. It is obvious that the line dividing the zone of light pollution from the zone

Table 88.- Number of Tubificidae and Hexagenia per square meter at twelve stations in a straight line from the mouth of Maumee River (Station 250) to a point twenty miles distant (Station 134) 1930. For location of stations consult Fig. 23.

Item	Station											
	250	251	252	253	254	255	256	257	258	259	260	134
Miles from mouth of Maumee River	0	2	4	6	8	9	10	12	14	16	18	20
Number of samples	6	5	6	3	6	1	3	2	2	3	3	8
Tubificidae	15,470	11,310	1,040	334	504	0	7	14	20	7	44	20
Hexagenia	0	2	37	34	63	108	402	182	634	564	337	462

of no pollution should be placed somewhere between Stations 254 and 256, and the small amount of evidence from Station 255 indicates that it should be placed between this point and Station 254.

At the remaining five stations in the series the counts of index organisms showed conditions typical of clean bottom. There was considerable variation in the counts, but the Tubificidae did not exceed 44 per square meter, and Hexagenia larvae were never less than 182 per square meter. The results obtained in this series are shown graphically in Figure 22.

In connection with the question of the outward extension of the area of polluted bottom, it is worthy of note that the outer end of the steamship channel is located almost exactly halfway between Stations 254 and 255, and thus marks the limit of the area of polluted bottom. A study of the charts of this region shows that the depths outside of the channel, near the outer end, are only slightly less than those in the channel, and the question arises whether a channel of such meager depth could operate as an important factor in determining the distribution of organic debris derived from the river nine miles away. In view of the slight depth of the channel near the outer end, one is led to answer the question in the negative, but the biological evidence presented in this section and in the section following indicates that the question should be answered in the affirmative. Osburn (1926) noted the importance of the channel in controlling the distribution of organic debris in Maumee Bay.

Pollution near the entrance to Toledo Harbor

Having determined the lakeward extent of polluted bottom along the line of the steamship channel, we may now consider the extent of pollution on the sides of the channel. Because of the dangers of navigation within the harbor outside of the channel, sampling was confined to stations located along lines across the entrance, that is, at the level of the outer end of the channel. Two series of stations were established at this level, one of three stations on a line running in a generally northwest direction from the end of the channel, the other of four stations on a line running in a generally southeast direction from the same point. The positions of these stations are shown in Figure 23. The results obtained, along with those from Station 254, are shown in Table 89. In order to simplify matters, the distances and directions are referred to Station 254, as though it were located at the end of the

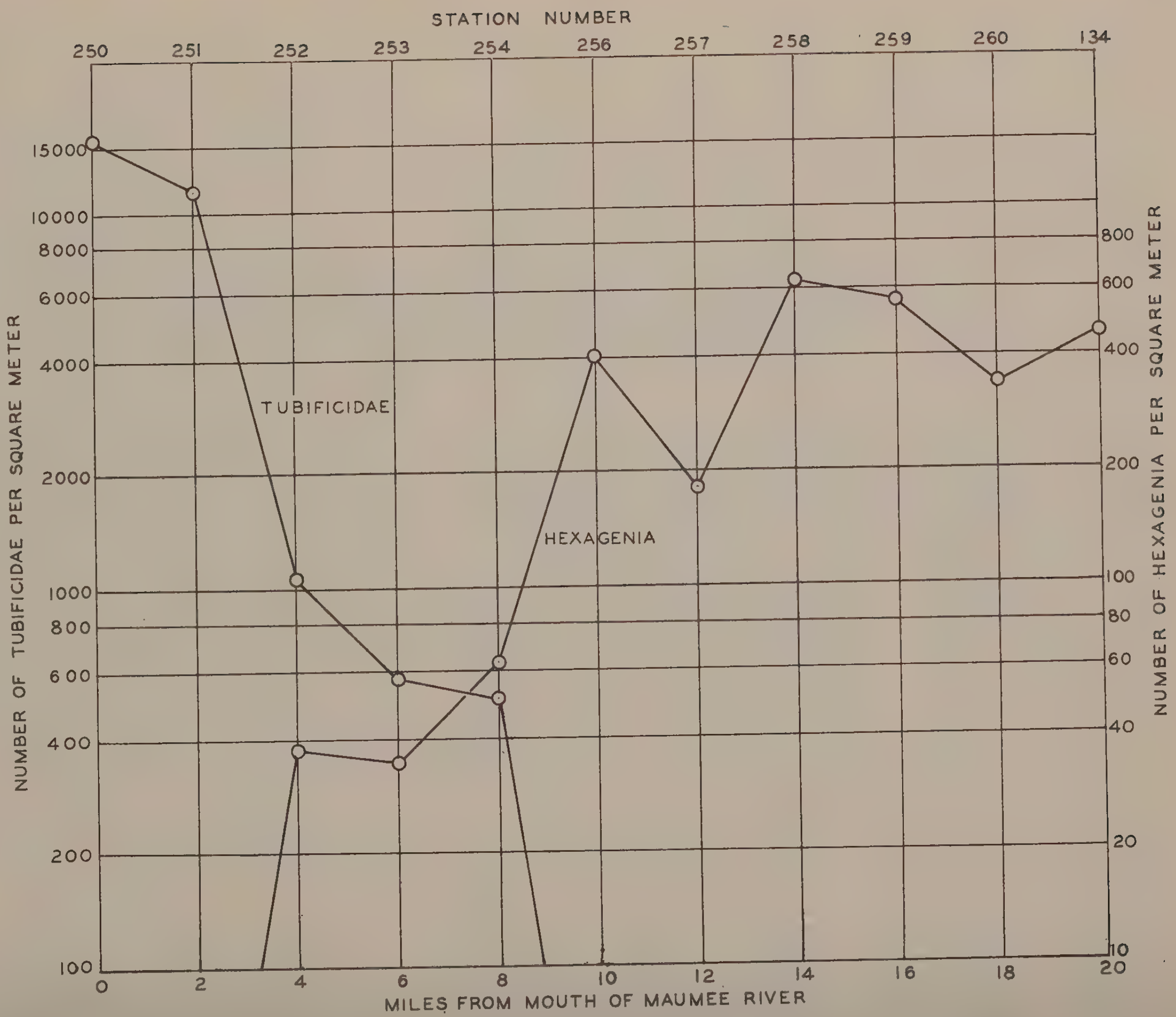

Fig. 22--Abundance of Tubificidae and Hexagenia at eleven stations along a line from the mouth of Maumee River to a the lake. The vertical scale is logarithmic. Data taken from Table 88.

channel. Actually it is one-half mile from the end.

Starting with Station 254, at the channel, we note again that there were 504 Tubificidae and 68 Hexagenia per square meter, indicating light pollution. At Station 110, one mile distant in a southeasterly direction, the single sample showed a total absence of Tubificidae, and the presence of 162 Hexagenia per square meter. At Station 109, two miles from the channel, the tubificid worms were also absent, and the mayflies were more abundant than at Station 110. Again at Station 107, four miles from the channel, no worms were found, but the mayflies were less abundant than at the previous two stations, a circumstance which is readily explained by the predominance of sand over mud in the bottom material. Three samples were taken at Station 105, located six miles from the channel. Here the bottom was predominatly mud rather than sand, and the difference is reflected in the greater number of Hexagenia. Tubificidae were present in traces. It is apparent that there is no evidence of pollution in the few samples taken in this series.

Further evidence of the fact that there is no eastward extension of pollution along the south shore is given in Table 90. This table gives the results obtained at six stations arranged in two series running out from the shore as shown in Figure 23. Tubificid worms were not found at any of the stations, and a fair number of Hexagenia was found at the stations where good samples could be taken. There need be no hesitation in assigning this area to the zone of clean bottom. The dividing line between it and the zone of light pollution would be placed, then, between Stations 254 and 110.

The three stations in the northwest series (Table 89) are represented by single samples in 1930. At Station 112 it was impossible to take a quantitative haul because of the bottom material, which was composed of hard clay overlain by sand and pebbles. It should be added that the single sample recorded in the table does not represent the total effort expended in an attempt to obtain a representative sample. At this station, and at many others to be recorded later, numerous unsuccessful hauls were made before the attempt was abandoned. The sample recorded for Station 112 was the final one. Enough of the bottom was taken to show that there was no accumulation of organic debris, and it is probable that few organisms were present. The single sample taken near this point in 1928 showed 86 Hexagenia per square meter and a considerable number of chironomid larvae, but no Tubificidae.

At Station 114, three miles from the channel, the bottom was composed of sand with an admixture of mud. The small number of Hexagenia can be explained by the small amount of mud in the bottom material. The

Table 89 .- Number of four kinds of bottom organisms per square meter at eight stations located on a line across the entrance to Toledo Harbor, 1930. For location of the stations consult Fig. 23.

Item	Station							
	105	107	109	110	254	112	114	116
Miles and direction from Station 254	6-SE	4-SE	2-SE	1-SE	0	1-NW	3-NW	5-NW
Kind of bottom	MS	SM	MS	MS	M	SC	SM	MS
Number of samples	3	1	1	1	6	[1]1	1	1
Tubificidae	14	0	0	0	504	0	68	0
Hexagenia	203	94	270	162	63	0	81	40
Chironomidae	50	148	68	40	98	14	14	540
Sphaeriidae	7	14	14	[2]540	[2]332	0	1134	14

[1] Hard bottom, sample not quantitative

[2] Mostly juvenile Musculium

Table 90 .- Number of four kinds of bottom organisms per square meter at six stations near Maumee Bay, 1930. For location of the stations consult Fig. 23.

Item	West series			East series		
Station	233	107	237	234	235	236
Miles from shore	½	2¾	4½	¾	2 7/8	5
Kind of bottom	C	SM	MS	SC	MS	MS
Number of samples	[1]1	1	1	[1]1	1	1
Tubificidae	0	0	0	0	0	0
Hexagenia	0	94	108	0	648	94
Chironomidae	68	148	14	0	0	0
Sphaeriidae	0	14	27	[2]0	0	162

[1] Hard bottom, impossible to take quantitative sample

[2] One specimen of Lampsilis taken

tubificid worms were noticeably more abundant than they were at stations in the Island Section, but still were below the number arbitrarily chosen as being indicative of pollution. At Station 116, the Tubificidae were absent, but the number of Hexagenia was small in spite of the predominance of mud on the bottom. More complete data were obtained in 1928, when five samples were taken on four dates. The mean counts per square meter were: Hexagenia, 145; Tubificidae, 27; and Chironomidae, 264. Thus, the evidence of clean bottom on this side of the channel is fairly conclusive in spite of the small number of samples, and the limit of the zone of light pollution may be placed between Stations 254 and 112.

It will be noted that Stations 110, 254, and 114 had rather large numbers of Sphaeriidae, mostly of the genus Musculium. Although Musculium transversum is known to be highly tolerant to pollution, its value as an index organism in the cases cited is largely discounted by the facts that a large majority were juvenile individuals, and that Musculium commonly has a "spotty" distribution. Certain of the stations, particularly Station 116, had large numbers of chironomid larvae as compared to stations in the Island Section. Since the species of chironomids were not determined, it is impossible to state whether there is any significance attached to their presence.

Summary statement regarding pollution in the Maumee Bay Section

In the summers of 1929 and 1930, a study was made of the nature of the bottom materials and their included animals at three stations situated on the steamship channel of Toledo Harbor. In 1930 the study was extended to a number of special stations, most of which were located in the neighborhood of the outer or lakeward end of the channel. A few samples were taken in 1928.

The results of this study may be summarized, in terms of the extent and degree of pollution, as follows. The bottom was heavily polluted from the mouth of Maumee River to a distance of about 3 1/2 miles along the steamship channel; it was moderately polluted for the next 1 1/2 miles, and lightly polluted for the remaining 4 miles to the outer end of the channel. There was no evidence of pollution at a distance of one mile in three directions from the outer end of the channel, or along the south shore of the lake east of Little Cedar Point. The extent of the three zones of pollution is shown in Figure 23. The question of the shoreward extension of the lines between zones is a matter of conjecture, since no data are available for that part of the harbor outside of the channel. The lines were extended to the shores in what appeared to be their most probable positions. No data are available for the area near the mouth of Ottawa River. The areas included in the zones of pollution as shown in Figure 23 are as follows: heavy pollution, 24.9 square kilometers (9.6 square miles); moderate pollution, 12.9 square kilometers (5.0 square miles); light pollution, 39.1 square kilometers (15.1 square miles). The total area of polluted bottom in the Maumee Bay Section was therefore 76.9 square kilometers (29.7 square miles). In view of the fact that the shoreward extensions of the zone-limits are not based on data, no importance should be attached to the decimals in the figures given above.

River Raisin Section

Station 117

The only regular station established in this section was Station 117, located 2 miles ESE 1/8 E of Monroe Light. The bottom at this point is composed of sand, with a small amount of gravel and organic debris. The results obtained in 1929 and 1930 are shown in Table 91. It may be seen that no organism or group of organisms was particularly abundant in either year. In 1929 the average count of Tubificidae was 21 per square meter, while in 1930 the average count was 104 per square meter. The mayfly larvae were rare in both years, but especially so in 1930. Their rarity is readily explained by the type of bottom; hence it cannot be taken as an index of the presence of pollution. Using the tubificid worms as the only index organisms, and applying the criteria of pollution as set forth in the introduction to this chapter, it is evident that this station should be assigned to the zone of clean bottom for 1929 and to the zone of light pollution for 1930.

In seeking an explanation for a similar difference in the data of the two years at Station 254, it was noted that the organisms were not uniformly distributed. However, at Station 117 there is no channel to confine organic debris derived from the river and give rise to unusually large differences in distribution of the organisms. The difference in the data of the two years probably resulted from actual shifting of the organic debris. The bottom is composed of sand and there is little opportunity for intimate mixing of the organic matter with the bottom deposits as in the case of mud bottom. Thus the accumulations of debris lying on the sand would be disturbed and moved about by currents and large waves. If it is true that there is a more or less constant shifting of the bottom materials, it is obvious that a few samples taken at one station would give a very incomplete picture of the situation with regard to pollution in this general area. For that reason, a considerable

Table 91.- Number of organisms per square meter at Station 117 in the River Raisin Section, 1929 and 1930

Item	Year	
	1929	1930
Number of samples	7	6
Hirudinea	7	3
Tubificidae	21	104
Hexagenia	57	8
Trichoptera	78	8
Chironomidae	107	55
Valvata	4	1
Amnicola	10	86
Goniobasis	18	18
Sphaerium	121	7
Musculium	0	0
Pisidium	4	39

number of special stations were established in 1930. The data from these special stations is discussed in the four following sections.

Extent of pollution out from the mouth of River Raisin

Table 92 shows the data obtained at ten stations located on a line from the mouth of the river to Station 134, at a distance of 11 miles. The table is self-explanatory, and mention need be made of only a few of the less obvious points and the conclusions to be drawn from the data. The deposits at Station 200 were similar to those found at the mouth of Maumee in 1929, but contained more sand, and organic debris of a woody nature, and less sludge-like material and oil. The odors were less putrid also. The number of Tubificidae at Stations 200 and 211 indicate a change from heavy pollution to moderate pollution within a half mile of the river's mouth. Judging by the single sample at Station 210, the dividing line should come between Stations 210 and 211. At Station 213, one-half mile farther out in the lake, the number of Tubificidae indicate clean bottom, but at Station 117, one mile out from Station 213, there was a reversion to light pollution.

Thus the station two miles from the river was polluted more than the station one mile from the river, a situation not unusual in this general area, or near the mouth of Detroit River. The explanation is probably to be found in the shifting about of the organic debris. Another possible factor is that of the unevenness of the bottom. The shifting organic debris would tend to collect in depressions of the bottom, though these were only slightly lower than the surrounding area. Thus, if Station 213 were located on relatively high ground, it might show less pollution than a station farther from the river, but located in a slight depression.

At Station 264, two miles out from Station 117, the tubificid count in the single sample was low. In view of the very light pollution at Station 117 in 1930, and the absence of pollution in 1929, it is not unreasonable to suppose that the single sample is representative of the bottom in the vicinity of Station 264, at least to the extent of indicating the absence of pollution. At Station 263 and farther out the evidence for clean bottom is conclusive.

Table 92.- Number of five kinds of bottom organisms per square meter at ten stations along a line from the mouth of River Raisin (Station 200) to a point eleven miles distant (Station 134), 1930. For location of stations consult Fig. 23.

Item	Station									
	200	210	211	213	117	264	263	262	261	134
Miles from mouth of River Raisin	0	¼	½	1	2	4	6	7½	9	11
Kind of bottom	M	MS	M	MS	SG	SM	MS	M	M	M
Number of samples	4	1	4	4	6	1	2	2	2	8
Tubificidae	29,100	5,300	1,950	58	104	14	0	0	0	20
Hexagenia	0	0	2	74	8	27	317	358	344	462
Chironomidae	730	135	106	534	55	148	34	20	20	18
Sphaeriidae	442	109	120	170	46	0	54	14	47	42
Gastropoda	54	54	396	198	108	27	0	0	0	0

Pollution between Stations 117 and 254

In order to determine the extent of pollution southward from Station 117, a series of four stations was established on a line running toward Station 254. The data obtained from the single samples taken at the four stations are shown in Table 93. As far as they go they indicate that pollution extended southward about 3 miles. At 4 and 6 miles from Station 117 there were no Tubificidae. It is not clear why there should be so few Hexagenia larvae at Station 267, since the bottom material was mud and the station is about the same distance from the channel as Station 256, where they were abundant (Table 88). At Station 268, only 3/8 mile from Station 254, there were 162 tubificids per square meter.

Pollution inshore

In order to determine the extent of pollution along the shore north and south of River Raisin, samples were taken at ten stations situated on a nearly straight line through Station 200. A summary of the results obtained is shown in Table 94. It may be seen that Station 200, at the river's mouth, was the only one showing heavy pollution, although at Station 214, 1/4 mile south, the number of tubificid worms in the single sample was at the upper limit of the range for moderate pollution. In the next 1/4 mile the number dropped sharply to 216 per square meter, indicating light pollution. No samples were taken between Stations 215 and 116F because of the presence of sand-bars which made navigation hazardous. The data from the latter station shows that light pollution extended southward from the river at least two miles. That it did not extend much farther is known from the records of samples taken at Stations 116D, 216, 217, and 218, which are not shown in the table. Station 116D is located two miles southwest of Station 116F, and the others are located at half-mile intervals on a line running from Station 116D toward the shore (Figure 23). At all of these stations the bottom was composed of hard gray clay overlain by clean sand which contained very few animals. Hence the southern limit of the polluted area may be placed about 3 miles from the mouth of the river.

On the north side of the river we find another example of a station near the river (Station 201) having a lower tubificid count than a station farther away (Station 202). Since the latter is represented by three samples as compared with a single sample at Station 201, we are justified in regarding the zone of moderate pollution as extending to a point between Station 202 and 203. Judging by the record of three samples at Station 204, pollution extended northward to a distance of less than one mile. At distances of two and three miles, the bottom was hard, composed of clay or solid rock, and there were no accumulations of organic

Table 93 .- Number of Tubificidae and Hexagenia per square meter at six stations in a straight line between Station 117 and Station 254, 1930. For location of the stations consult Fig.23.

Item	Station					
	117	265	266	267	268	254
Miles from Station 117	0	2	4	6	8	8 3/8
Kind of bottom	SG	S	SM	MS	M	M
Number of samples	6	1	1	1	1	6
Tubificidae	104	108	0	0	162	504
Hexagenia	8	0	27	68	40	63

Table 94.- Number of five kinds of organisms per square meter at ten stations along a five-mile line running north and south through the mouth of River Raisin, 1930. For location of stations consult Fig. 23.

Item	Station									
	116 F	215	214	200	201	202	203	204	205	206
Miles and direction from mouth of River Raisin	2-S	½-S	¼-S	0	¼-N	½-N	¾-N	1-N	2-N	3-N
Kind of bottom	M	SM	MS	M	MS	MS	SM	SM	C	R
Number of samples	1	3	1	4	1	3	1	3	[3] 2	[3] 1
Tubificidae	270	216	5000	29,120	216	1,610	513	41	0	0
Hexagenia	14	32	0	0	0	49	0	18	14	0
Chironomidae	40	144	256	780	176	225	108	333	7	0
Sphaeriidae[1]	68	310	756	442	68	208	81	278	0	0
Gastropoda[2]	0	87	122	54	0	145	81	267	20	0

[1] Mostly Musculium, juvenile and adult

[2] Mostly Bithynia, Valvata, and Amnicola

[3] Hard bottom, impossible to take quantitative sample

atter. The records of Stations 207, 208, and 209, not shown in ables, also yielded no evidence of pollution.

Pollution offshore

Table 95 shows the results obtained at ten stations located n a straight line from a point near Toledo Beach (Station 116) to a oint near the mouth of Detroit River (Station 126). The line has a north-ast-southwest trend and lies off the shore at a distance varying from 1/4 to 3 1/2 miles. All of the stations except the regular ones (117 and 26) are represented by single samples. These meager data indicate that he Tubificidae were confined to the area off the mouth of River Raisin and o the station nearest the mouth of Detroit River. Based on these data, he line limiting the zone of light pollution would be drawn between tations 116F and 116D on the southwest, and between Stations 117 and 118 n the northeast. A discussion of conditions in the vicinity of the outh of Detroit River appears in a later section of this paper.

Summary statement regarding pollution in the River Raisin Section

A study of the bottom organisms at a large number of stations in he vicinity of River Raisin was carried on in the summer of 1930 to upplement the small amount of data obtained at one station in 1929. The onclusions may be summarized briefly as follows. The zone of heavy pollu-ion was small in extent, reaching no farhter than 3/8 mile out into the ake, and probably not more than 1/8 mile north and south from the mouth f the river. It is estimated that the outer limit of the zone of moderate ollution extended 3/4 mile out into the lake, 3/8 mile along the shore oward the south, and 5/8 mile along the shore toward the north. The uter limit of the zone of light pollution extended approximately 2 3/4 iles out into the lake, 2 1/2 miles along the shore toward the south, and mile toward the north. At a distance of 2 miles lakeward from the iver's mouth (Station 117) the northward and southward extension of this one was about the same as it was near the shore. The extent of the hree zones is shown graphically in Figure 23. Because of the small pace available, only the zone of light pollution was labelled on the map. he zone of heavy pollution is enclosed by the elliptical line at the outh of the river, and the zone of moderate pollution lies between this ine and the zone of light pollution. The areas are: heavy pollution, .3 square kilometer (0.1 square mile); moderate pollution, 2.1 square ilometers (0.8 square mile); light pollution, 30.3 square kilometers

Table 95.- Number of five kinds of bottom organisms per square meter at ten stations along a straight line from a point near Toledo Beach (Station 116) to a point near the mouth of Detroit River (Station 126), 1930. For location of stations consult Fig. 23.

Item	Station									
	116	116D	116F	117	118	119	121	123	125	126
Miles and direction from Station 117	6½-SW	4-SW	2-SW	0	1-NE	2-NE	4-NE	6 1/8-NE	8¼-NE	9½-NE
Kind of bottom	MS	CS	M	SG	SM	SM	M	CM	SM	MS
Number of samples	1	[1]1	1	6	1	1	1	[1]1	1	5
Tubificidae	0	0	270	104	40	0	0	0	0	205
Hexagenia	40	0	14	8	0	162	0	0	0	0
Chironomidae	540	68	40	55	1593	68	0	0	0	60
Sphaeriidae[2]	14	0	68	46	0	28	14	108	702	1108
Gastropoda	0	14	0	108	96	54	40	162	69	60

[1] Hard bottom, sample not strictly quantitative

[2] Mostly Sphaerium

(11.7 square miles). The total area of polluted bottom in this section in 1930 was therefore 32.8 square kilometers (12.6 square miles).

Detroit River Section

Regular Stations

Only two regular stations were established in what has been designated as the Detroit River Section. One of these is Station 126, located very close to the outer end of the west or down-bound channel as the latter was situated in the summer of 1929. Before sampling was begun in 1930, dredging operations had extended the channel southward about 6000 feet, but apparently had not disturbed the bottom at Station 126. The bottom material at this station was composed principally of mud, with an admixture of sand and organic debris. Judging by odor, and general appearance of the residue following washing, the amount of decaying organic matter was much less here than at the mouths of Maumee and Raisin Rivers.

The results obtained from 16 samples taken in 1929 and 5 samples taken in 1930 are shown in Table 96. It is obvious from the number of Tubificidae and the absence of Hexagenia that this station was lightly polluted in both years. In view of the fact that in 1930 Station 254 (Toledo Harbor Light) had quite a number of Hexagenia along with 504 tubificids per square meter, it appears probable that the absence of Hexagenia at Station 126 was due to the presence of considerable sand rather than to the degree of pollution. Comparing counts for the two years at Station 126, it will be noted that the total number of individuals was greater in 1929 than in 1930. This difference resulted from an apparent small increase in three of the groups and a rather large increase in five of the groups represented. In 1928, 8 samples were taken on two dates. The means for the two dates were 150 Tubificidae and 182 Chironomidae per square meter. Only a few other forms were taken.

The second regular station is Station 134, located 6 1/4 miles due west of Middle Sister Island, which places it 8 miles S. by E. from Station 126. Here the bottom material was mud of the same appearance and consistency as that found at the regular stations in the Island Section. The results obtained from 12 samples in 1929 and 8 samples in 1930 are shown in Table 96. There was no evidence of pollution at this station; the tubificid count was well below the number considered indicative of pollution, and the mayfly count was high, especially in 1930. The general make-up of the bottom fauna was much like that of

Table 96.– Number of bottom organisms per square meter at Stations 126 and 134 in the Detroit River Section, 1929 and 1930

Item	Station			
	126		134	
Year	1929	1930	1929	1930
Number of samples	16	5	12	8
Hirudinea	41	79	4	18
Tubificidae	457	205	52	20
Hexagenia	0	0	154	462
Trichoptera	0	0	0	0
Chironomidae	29	60	26	18
Bithynia	14	16	0	0
Valvata	269	11	0	0
Amnicola	129	27	4	0
Sphaerium	1112	411	31	36
Musculium	514	116	10	0
Pisidium	233	57	1	2
Sphaeriidae (juvenile)	—	524	—	4

stations in the Island Section, and the counts might well have been included in the averages for thtat section, but in the interest of consistency with other chapters in this report, the station has been retained in the Detroit River Section. The differences in the fauna here as compared with Station 126 are too obvious to require mention.

Pollution in the Detroit River Section

As in the case of the Maumee Bay Section and the River Raisin Section, an attempt was made to determine the degree and extent of pollution in the Detroit River Section by taking bottom samples at a number of special stations in 1930. The problem of defining the limits of pollution in this section is somewhat more difficult than in the other sections because the wide mouth and voluminous discharge of the river have permitted the diffusion of suspended organic debris over a large area having different types of bottom. Since most of the stations near the outer edge of the polluted area were sampled only once, and since the organic debris was certainly distributed unevenly, the basis for conclusions regarding the position of this outer edge must be regarded as relatively insecure. Even though the data must be considered inadequate, it seems probable that any errors (in terms of area) arising from their use would be small compared with the total area of Western Lake Erie.

Table 97 shows the results obtained at 10 stations located on a course from Bois Blanc Light in Detroit River (Station 219) to a point in the lake 16 miles distant (Station 134), as shown in Figure 23. The samples taken at the first four stations revealed considerable variation in the type of bottom and in the abundance of the index organisms. These marked variations probably resulted in part from the dredging operations carried on from time to time by governmental agencies. Such operations would tend to make the bottom markedly uneven, and since the current is rather strong in this area, organic debris would be swept from high points and would settle in depressions. Also the current would tend to keep debris in suspension for some distance out into the lake, where its strength would be dissipated and the debris deposited. That such a thing actually happened is suggested by the fact that there were fewer tubificid worms at Station 219 than at four stations below it. It may be mentioned here that single samples were taken at two stations not shown in the table. These were 221A and 221B, located one and one-half miles east and one mile west, respectively, of Station 221. At Station 221A the bottom was composed

Table 97 .- Number of bottom organisms per square meter at ten stations in a line from Bois Blanc Light, in Detroit River (Station 219), to a point sixteen miles distant (Station 134), 1930. For location of the stations consult Fig.23.

Item	Station									
	219	220	221	222	126	127	128	130	132	134
Miles from Bois Blanc Light	0	2	4	6	8¼	9½	10½	12½	14½	16½
Kind of bottom	MSG	MS	MS	SM	MS	S	M	M	M	M
Number of samples	3	4	4	4	5	1	3	2	1	8
Tubificidae	122	933	162	1500	205	14	221	14	0	20
Hexagenia	203	13	101	0	0	0	13	21	310	462
Chironomidae	189	47	58	9	60	0	54	0	0	18
Sphaerium	283	142	398	149	411	0	126	54	14	36
Musculium	0	7	10	142	116	0	0	0	0	0
Pisidium	36	[1]2	7	[1]83	[1]57	0	0	0	0	2
Gastropoda	63	0	10	61	60	0	5	0	0	0

[1] Also numerous juvenile Sphaeriidae

of hard clay and no adequate sample could be taken. At Station 221B there were 702 Tubificidae per square meter and Hexagenia larvae were absent. Obviously a separate investigation would be necessary to determine the distribution of organisms in this general area.

The Tubificidae were most abundant at Station 222, located at Detroit River Light, about three miles out from the mouth of the river as defined in this report. The count of 1500 worms at this point indicates moderate pollution. But at Station 126, two miles below, the counts of 1929 and 1930 show that the bottom was only lightly polluted. In spite of the apparent inadequacy of the data at Station 222 and in the lower part of the river, it seems reasonable to assign this are to the zone of moderate pollution and to draw the line of demarcation (between it and the zone of light pollution) between Stations 222 and 126.

Sand bottom was encountered at Station 127, probably as a result of dredging operations at the time the down-bound channel was extended southward. Only a few tubificids were taken. At Station 128, one mile farther out, the bottom was composed of mud and the tubificid count was again in the range of light pollution and there were a few Hexagenia larvae. At Station 130, located two miles from the preceding station, the mayfly larvae were still few in number in spite of the very low tubificid count. In accordance with the policy of using only the Tubificidae in case of conflicting evidence, the line separating the zone of light pollution from the zone of clean bottom would be placed between Stations 128 and 130. At Stations 132 and 134 the bottom was obviously free from pollution. A single sample taken at Station 131 (half way between Stations 130 and 132) in 1928 yielded 430 Hexagenia per square meter.

In order to determine the extent of pollution to the west and northeast of Station 126, six special stations (239, 240, 241; 223, 224, and 225) were established as indicated in Figure 23. The data obtained are shown in Table 98. Only one of the six stations had bottom soft enough to yield a sample which could be regarded as quantitative. This was Station 240, located 2 miles west of Station 126. Here there were 122 Tubificidae per square meter but no Hexagenia, indicating very light pollution. In view of the negative results obtained at Stations 241 and 239, and at other nearby stations (Table 95), it seems advisable to place the line of demarcation between Stations 240 and 241. It must be admitted, however, that further collecting might require a change in its position. Toward the northeast from Station 126 it was found impossible to take a good sample of the bottom, but there was no evidence of organic debris.

Table 98.- Number of five kinds of bottom organisms per square meter at six stations near the mouth of Detroit River, 1930. For location of the stations consult Fig. 23.

Item	Station						
	241	240	239	126	223	224	225
Miles and direction from Station 126	3-W	2-W	1-W	0	2-NE	4-NE	6-NE
Kind of bottom	SG	MS	S	MS	R	SG	S
Number of samples	[1]1	1	[1]1	5	[2]2	[2]2	[1]2
Tubificidae	0	122	0	205	0	0	0
Hexagenia	0	0	0	0	0	0	0
Chironomidae	81	54	0	60	0	0	0
Sphaeriidae[3]	0	324	392	1108	0	0	7
Gastropoda	0	54	54	60	0	0	27

[1] Hard bottom, samples not quantitative

[2] Hard bottom, no organisms taken

[3] Mostly juvenile

The results obtained from seven other special stations in the area east of Station 126 are shown in Table 99. The location of these stations is indicated in Figure 28. At Station 232, located two miles approximately southeast of Station 126, the single sample showed 189 Tubificidae per square meter but no Hexagenia larvae, indicating light pollution. The next three stations along the same course (Stations 231, 230, and 229) yielded no evidence of pollution. At Station 228, located two miles north and slightly west of Station 229, the Tubificidae were present in small numbers, as were the mayfly larvae. Two miles farther on the same course (Station 227) there was definite evidence of light pollution. At Station 226, located halfway between Stations 227 and 225, there were few organisms of any kind, but the mud had a distinct oily appearance and odor. On the basis of the small amount of data from this region, the line of demarcation between the zones of light pollution and clean bottom should be placed between Stations 232 and 231 in the southeast series, and between Stations 227 and 228 in the north series. When so placed, the zone of light pollution includes three stations (Stations 223, 224, and 225) at which no evidence of pollution was found. The bottom was firm at each of these stations, and it is probable that a considerable area about them had the same type of bottom. The current of the river doubtless was responsible for the failure of organic debris to lodge on the bottom, but it is not clear why other stations, such as Station 222, were not affected in the same way.

Summary statement regarding pollution in the Detroit River Section

Samples were taken at two regular stations in both years and at a number of special stations in 1930. Because of the large area affected by pollution and the irregular distribution of the organic material, it was not found possible to determine the limits of pollution as confidently as in the case of Maumee Bay Section and River Raisin Section. No evidence of heavy pollution, as defined in this report, was found in the river itself or in the lake near its mouth. The only station which showed moderate pollution was located approximately three miles out from the mouth of the river, but all of the area above this was assigned to the zone of moderate pollution. It was estimated that the outer edge of the zone of light pollution extended a distance varying from 3 1/2 to 7 1/2 miles from the mouth of the river. An unknown but considerable part of

Table 99.- Number of Tubificidae and Hexagenia per square meter at eight stations near the mouth of Detroit River, 1930. The directions given are only approximate. For location of stations consult Fig. 23.

Item	Station							
	126	232	231	230	229	228	227	226
Miles and direction from preceding station	0	2-SE	2-SE	2-SE	2-SE	2-N	2-N	2-N
Kind of bottom	MS	M	M	M	M	M	M	MS
Number of samples	5	1	1	1	1	1	1	1
Tubificidae	205	189	0	0	0	27	297	40
Hexagenia	0	0	176	189	634	81	14	0

the area within the outer limit of the zone of light pollution had a bottom free from organic debris. The conclusions regarding the extent of the two zones of pollution are shown in Figure 28; their areas are as follows: moderate pollution, 31.3 square kilometers (12.1 square miles); light pollution, 122.0 square kilometers (47.1 square miles). The total area is 153.3 square kilometers (59.2 square miles).

Areas of the zones of pollution

Table 100 shows the areas included in the zones of heavy, moderate, and light pollution at the mouths of Maumee, Raisin, and Detroit Rivers. These areas were obtained by the use of a polar planimeter on the large-scale map from which Figure 23 was reproduced. Only at the mouths of Maumee and Raisin Rivers was there heavy pollution as defined in this report, and at River Raisin the area of the zone was very small. The area of moderately polluted bottom also was small at the mouth of this river, but at the other two rivers considerable areas were included, making a total of 46.3 square kilometers (17.9 square miles), as compared to a total of 25.2 square kilometers (9.7 square miles) for the zones of heavy pollution. The zones of light pollution were the largest in each section; the combined area was 191.4 square kilometers (73.9 square miles). The areas of the three zones combined for each section were as follows: Maumee Bay Section, 76.9 square kilometers (29.7 square miles); River Raisin Section, 32.7 square kilometers (12.6 square miles); Detroit River Section, 153.3 square kilometers (59.2 square miles); giving a grand total of 262.9 square kilometers (101.5 square miles), or 7.7 per cent of the water area of Western Lake Erie exclusive of Sandusky Bay. Of the area within the zones of pollution, 72.8 per cent fell within the zone of light pollution, and an unknown but considerable part of this zone was free of organic debris.

Effects of pollution on the fishery

General Statement

The extent and degree of pollution in Western Lake Erie has been determined with some degree of exactness, but interpretation of the facts in terms of the effects on the fishery must be based largely on conjecture. Some of the effects of pollution are harmful to fishes and hence to the fishery, while others are clearly advantageous. However, there are no standards by which they can be compared quantitatively to determine the residual effect on the fishery.

Table 100 .- Areas included in zones of heavy, moderate, and light pollution, 1930. Areas determined by planimeter on the original map from which Fig. 23 was reproduced

Zone of pollution	Section						Total	
	Maumee Bay		River Rasisin		Detroit River			
	square kilometers	square miles	square kilometers	square miles	square kilometers	square miles	square kilometers	square miles
Heavy	24.9	9.6	0.3	0.1	0.0	0.0	25.2	9.7
Moderate	12.9	5.0	2.1	0.8	31.3	12.1	46.3	17.9
Light	39.1	15.1	30.3	11.7	122.0	47.1	191.4	73.9
Total	76.9	29.7	32.7	12.6	153.3	59.2	262.9	101.5

The interactions between fishes and their environment is extremely complex in natural waters, and are much more complex in waters contaminated by domestic and trade wastes. Since our knowledge of the relationships under natural conditions is far from complete, it is hardly to be expected that an unqualified statement can be made concerning them in polluted waters.

In spite of the complexity of the problem and the incompleteness of our knowledge, certain conclusions with regard to possible effects of pollution on the fishery seem to be justified. It is not to be supposed that the writer considers the conclusions final in the sense that the facts admit of no other interpretation. On the contrary, an attempt will be made to consider a number of possible interpretations of the known facts. It may be well to state in advance that it seems highly improbable that pollution in Western Lake Erie has been the primary or controlling factor in depletion of the fishery. The reasons for this conclusion will be given in the discussion to follow.

Chemistry

There is in existence an extensive literature on the general subject of the relationship of fishes to the chemical characteristics of the water in which they live. Even a cursory examination of this literature leads one to the conclusion that tolerance of fishes to unfavorable chemical conditions is extremely variable. It varies between species, in the same species at different ages, and in the same species of the same age under different physical conditions. For that reason it is quite impossible to determine any one figure for oxygen concentration above which fishes will live and below which they will die. Fishes may live for some time in water devoid of oxygen, and under certain conditions may die rapidly in water with a high content of the gas. The whole problem of the relationship of fishes to their chemical environment is so complex, particularly in polluted waters, that it seems inadvisable to adopt arbitrary standards for purposes of discussion in this report. The discussion, of necessity, will be made general.

It has been shown that the water of the Island Section could be regarded as practically unpolluted, as far as pollution would affect the content of dissolved oxygen and the associated chemical characteristics. At one time during the three years in which chemical determinations were made in the open lake, low oxygen was found in the lower water. At Station 59A on August 9, 1930, at a point one meter above bottom, the oxygen content was 0.78 part per million or 8.6 per cent of saturation. The water in contact with the bottom probably was devoid of oxygen, but the stratum low in oxygen seems to have been restricted to the lowermost three meters of water. Temporary thermal stratification was the indirect cause of the change in chemical conditions. Stratification was established not more than two weeks prior to the time of sampling and probably was destroyed one or two days after sampling. The area affected apparently was small, for there was no thermal stratification farther west at that time.

There is no reason to believe that the reduction of oxygen resulted from other than natural causes. Nor is there reason to believe that fishes of the region were harmed. The amount of oxygen available was so small that it probably would have been fatal to any that remained, but it is well known that fishes can and do avoid waters low in oxygen. Thus, in Lake Mendota the yellow perch regularly moves out of the hypolimmon during the summer period of stagnation, although it may return for short periods (Pearse and Achtenberg, 1920).

Only one station in the entire area studied showed low oxygen and high free carbon dioxide on every date for which samples were taken. This was Station 249, about five miles above the mouth of Maumee River. On the five dates in 1930 for which data are available, the oxygen content ranged from 2.9 to 4.4 parts per million and from 34 to 49 per cent of saturation. At the mouth of the river, oxygen was sometimes low and sometimes high as a result of the reversals of current in the river. In 1929 and 1930, it ranged from 1.0 to 10.5 parts per million and from 12 to 112 per cent of saturation. There were no marked oxygen reductions at a distance of 2.25 miles from the mouth of the river. At the mouth of River Raisin in 1930 oxygen ranged from 0.0 to 9.0 parts per million and from 0 to 98 per cent of saturation. The lower one mile of the river in 1920 usually showed less than 50 per cent of saturation, and sometimes much less than that amount. No cases of marked oxygen reductions were noted at a distance greater than one half mile out in the lake.

In the two rivers mentioned, and in small areas near their mouths, conditions with respect to oxygen and carbon dioxide were commonly such as to be unfavorable for the normal existence of fishes. It is not to be supposed that fishes were entirely excluded from such regions. Professor Reighard, in his unpublished report on River Raisin, noted the presence of considerable numbers near sewer outfalls. However, they were principally species which appear to be tolerant to polluted situations, such as the blunt-nosed minnow, the golden shiner, and the gold-fish. The pure-water types were rare. It is not unlikely that conditions in the lower part of Maumee River also exclude the pure-water types but allow the more tolerant ones to remain. There were no areas other than those mentioned where unfavorable chemical conditions were found, although without doubt they exist in Detroit River near sewer outfalls. Such areas probably constitute a small part of the total area available to the fishes in the river.

It is difficult to evaluate conditions with respect to oxygen and carbon dioxide in terms of their effect on the fishery of the lake, but it is doubtful whether fishes have been killed in large numbers by such conditions. As mentioned previously, they are able to migrate from waters low in oxygen, and thus escape the more serious effects. The undesirable effect, then, seems to have been the reduction of the area available to those species which require an abundant supply of oxygen. If space were a limiting factor, this reduction could be considered as positively harmful to the fishery. However, in view of the small area adversely affected, it is questionable whether space has limited the number of fish which the lake can maintain. If this question be answered in the negative, then the only obvious harmful effect would be the additional expense and inconvenience to fishermen in setting nets farther from their base of operations in the polluted areas. As an offset to this, may be mentioned the possibility that conditions in the polluted areas have resulted in an increase of the more tolerant, although less desirable, species. On the whole it seems improbable that low oxygen and the associated chemical characteristics has been an important factor in depletion of the fishery.

It will be necessary to consider another factor, namely, the presence of poisonous chemicals derived from industrial wastes. Evaluation of this factor is even more difficult because of our nearly total lack of knowledge of the kind and abundance of poisons present. Conclusions must be made with caution because it is well known that certain chemicals may be harmful to fishes in extremely dilute solution.

In all probability, strong alkalies and acids were not present in high concentration, for determinations of acidity or alkalinity to phenolphthalein, and of pH, were never extremely high or extremely low. The work of Donaldson and Furman (1927) shows that phenol was present in less than one -half of the samples taken near Toledo Harbor Light and near the mouth of Detroit River. The maximum amount found was 52 parts per billion. Shelford (1917, p. 395) reported that a concentration of 70-75 parts per million was required to kill a small sunfish in one hour. Donaldson and Furman found that the strongest waste entering Maumee River contained 38 parts per million, or about one half of the amount necessary to kill the sunfish in one hour. Dilution by river water would lower the concentration rapidly. However, it is unsafe to conclude that the waste could not kill fishes, for Shelford (page 403) found that several species reacted positively to concentrations which would kill them in two or three hours. It seems unlikely that large numbers would be killed in Maumee River, although many might be affected adversely. Van Oosten (1929) reported that, in Saginaw Bay, the growth rate and quality of flesh of fishes were affected by dichlorobenzol released in Saginaw River, 40 miles above the mouth.

While there are almost infinite possibilities of fishes being harmed by trade wastes in Maumee and Raisin Rivers, it is by no means certain that they have been harmed to any great extent. The facts that Professor Reighard reported numerous fish in lower River Raisin, and that fishermen set their nets just outside the mouth of Maumee River, shows that poisons are not regularly present in lethal concentrations.

Another point of considerable importance in this connection is that there was a direct relationship between the abundance of plankton, both plant and animal, and the intensity of pollution as indicated by the chemical determinations. It is reasonable to suppose that concentrations of chemicals which would be harmful to fishes would also be harmful to plankton organisms. For that reason it is difficult to believe that the very large numbers of algae and crustacea found in Maumee Bay in 1930, could have existed in the presence of trade wastes of sufficient concentration to be of great harm to fishes.

It must be evident from the foregoing discussion that the available data prove nothing with regard to the effect of chemical pollution on the fishery. However, the presence of water low in oxygen and high in free carbon dioxide, even in restricted areas, hardly can be regarded as a desirable condition. The presence of poisonous trade wastes is even less desirable. In the opinion of the writer chemical pollution probably has been harmful to the fishery, but it seems equally probable that it has not been the primary factor in depletion. The possible advantage to the fishery resulting from the addition of large quantities of soluble nutritive materials will be considered in a later section.

Bacterial pollution

In 1929, this investigation included a study of bacterial pollution in Western Lake Erie and its tributaries by Dr. William C. Beaver.

For various reasons the results were not presented in this report but it seems advisable to state the general conclusions reached. The tributaries studied were heavily polluted by sewage bacteria. In the lake, only those parts near Detroit River and Maumee River were heavily polluted and the intensity of pollution decreased rapidly with increased distance from their mouths. Parts of the lake far from known sources of pollution were only intermittently polluted, and on the average were much less heavily polluted than the tributaries or parts of the lake near the large tributaries.

Those interested in published reports on baceterial pollution in the Great Lakes may refer to the following: Crohurst and Veldee (1927), Detroit Department of Water Supply (1930), Ellms (1922 and 1931), Follin (1916), Gottschall (1930), International Joint Commission (1914, 1918 and 1918a), Jackson (1912), Mohlmann and Ruchhoft (1927), Ohio State Board of Health (1889 and 1902), Osburn (1926 and 1926a), Streeter (1930), Whipple (1902 and 1913), Zillig (1929).

The United States Tariff Commission (1927, p. 2 ff.) made some broad assumptions with regard to the role played by pollution in depletion of the fisheries. Representatives of 95 per cent of the fishing companies on the south shore of the lake and 12 per cent on the Canadian shore stated to the commission's experts that pollution affected their supply of fish. It was then concluded that the findings of the International Joint Commission (1914), with regard to pollution in 1913, substantiated the testimony of the companies. The conclusion is wholly unjustified. The Tariff Commission obviously misinterpreted the aims of the International Joint Commission as well as the significance of its findings. The bacteriological survey of 1913 was made in the interest of public health, and the data obtained tell us nothing of the effect of pollution on fishes. A body of water may be unsafe as a source of drinking water for human beings and yet be entirely safe for fishes. There are no known bacterial diseases common to fishes and man, according to Plehn (1924, page 452). It is probably true that bacteria which attack fishes are more abundant in water polluted by domestic sewage than in unpolluted water, because of the additional nutritive materials available, but it is unsafe to conclude, without evidence, that such pollution is a factor in the depletion of a fishery. No investigation has been made of bacterial diseases of the fishes of Western Lake Erie, but there is no reason to believe that the fishes are unusually subject to such diseases.

Pollution of the bottom

Studies of mud bottom in the Island Section gave no evidence of pollution. The principal organism present was Hexagenia, a burrowing mayfly which is known to be intolerant to bottoms covered by organic debris or sludge. There is good reason to believe that conditions in that section of the lake are now as favorable for Hexagenia as they ever were. Absence of sludge deposits in the relatively deep parts of the Island Section justified the conclusion that they were absent from the wave-swept shoals and reefs, and this conclusion was confirmed as far as possible, by qualitative samples taken with the bottom-sled on the shallow offshore areas. Such qualitative studies revealed large areas with a firm bottom composed of sand, gravel, or boulders. All of the available evidence leads to the conclusion that there have been no spawning grounds rendered unfit for use, and that the food relations of bottom-feeding fishes have not been adversely affected.

Bottom-feeding fishes should find conditions on mud bottom particularly favorable because of the abundance of mayfly larvae. Rawson (1930, pp. 125-133) found ephemerid larvae to be an important item in the food of certain fishes in Lake Simcoe. Although these insects made up only 5.8 per cent of the bottom fauna, they formed 30 per cent of the food of the whitefish, and nearly one half of the food of the perch and common sucker. The fact that Lake Simcoe and Lake Nipigon support large numbers of bottom-feeding fishes (Rawson, 1930; Dymond, 1926) in spite of the small population of bottom organisms (Table 123), suggests that the Island Section of Lake Erie could still support as large a population of bottom-feeders as it has in the past.

Only at the extreme west end of Western Lake Erie, near the mouths of Maumee, Raisin and Detroit Rivers, was there evidence of the deposition of organic debris. The areas affected are shown in Fig. 23 and Table 100. Aside from the presence of organic matter, the most obvious difference between these areas and the Island Section, was the great abundance of tubificid worms and the rarity or absence of Hexagenia, Sphaeriid molluscs and chironomid larvae also were abundant, but were less constant in occurrence than the tubificids.

There arises the question of the availability of food for bottom-feeding fishes in the polluted areas. The actual production of living material unquestionably has increased in those areas, but the increase has taken place to a considerable extent in the tubificid worms, which Richardson (1928, pp. 444-453) regarded as of minor importance because of inaccessibility. He believed that they would be eaten in numbers only by the large bottom-feeders (carp, buffalo, and other sucker-mouthed fishes) when they took up the larger bottom organisms such as Sphaeriidae. If such fishes in Western Lake Erie ingest large numbers of the worms along with the Sphaeriidae, it is possible that they would find a larger supply of food on the polluted bottoms than on the unpolluted bottoms. The carp obtains much of its food by rooting about in the mud (Cole, 1905, p. 567), and presumably it would ingest the worms, although Cole did not list tubificids as an item of food in the carp of Lake Erie. Stewart (1926, p. 180) pointed out that the adult sucker (Catostomus commersonii) holds large food particles in the mouth and rejects the sand before swallowing. Such a habit would result in the loss of many small organisms like the tubificid worms. Other bottom feeders such as the perch, catfish, and sheepshead are also more discriminating in their food habits than the carp and might profit little from the presence of the worms. The whitefish need not be considered in this connection because it is present in this area of the lake only during the spawning period, when it takes little or no food.

On the whole it seems probable that, even though the tubificids are not used to a great extent, the sphaeriid and other molluscs are abundant enought on polluted bottom to prevent a food shortage for the bottom-feeding fish.

Wide acceptance has been given to the idea that the decline of the whitefish (Coregonus clupeaformis) has resulted from pollution of its spawning grounds. Formerly the whitefish was extremely plentiful in Lake Erie. It spent most of the year in the deeper water east of the islands, but in autumn migrated westward to spawn. Large numbers entered Detroit River to spawn in the river, in Lake St. Clair, and even in St. Clair River. For many years the whitefish has not entered Detroit River in commercial quantities. Within recent years the Federal hatchery at Put-in-Bay has been unable to get sufficient eggs along the west shore of the lake to fill the hatchery. The fact that considerable numbers still spawn in the vicinity of the island makes the case against pollution a strong one. However, other possible explanations present themselves.

Rapid decrease in the abundance of whitefish in the Great Lakes had been noted prior to 1870 (Milner, 1874). In the last decade of the century the decline of the Lake Erie whitefish had become alarming. The fishery of Detroit River,described by Milner as highly successful, had been abandoned (Rathbbun and Wakeham, 1897, p. 116). These writers mentioned the possible effect of sewage pollution on the river fishery, but expressed the opinion that overfishing, both in the river and in the lake below it, was the principal factor involved (p. 116 and pp. 101 - 102). This suggests the possibility that there are distinct strains or races of whitefish, and that the one which formerly spawned on the west shore of the lake and in Detroit River has become commercially extinct through overfishing. Or this race may have changed its migration behavior for some reason other than pollution. The whitefish has shown marked changes in migration from time to time (Michigan Fisherman, 1928), and it is known that a related fish (Leucichthys artedi) became almost commercially extinct as an indirect result of a change in its habits of migration (Van Oosten, 1930). Another possible factor in the decline in the whitefish is that of competition for spawning grounds with the introduced carp (Cyprinus carpio).

The brief discussion given above is sufficient to show that pollution of the spawning grounds is not the only possible factor in the depletion of the whitefish. It is worthy of note that the whitefish was on the decline in early times, when pollution of the bottom must have been very light. Thus Milner (1874) reported depletion of the supply in St. Clair River prior to 1870, and, as mentioned before, the fishery of Detroit River was abandoned before 1897. In 1890 the population of Detroit was only 205,876, and the total population contributing sewage to the river probably was not more than one fourth of the number in 1930. In the light of our knowledge of the extent and degree of pollution in 1930, it seems highly improbable that pollution was sufficiently intense before 1900 to account for the observed decline.

It is impossible to determine how large an area of bottom once suitable for spawning has been made unsuitable by the deposition of sludge. No one will object to the statement that parts of the area now polluted never were used as spawning ground. The deposition of silt carried by the rivers would make parts of the lake unfit for such purposes. This would be true particularly in Maumee Bay, because of the protection from strong winds and currents. Near River Raisin and Detroit River littoral currents and waves would tend to keep the bottom scoured clean. Yet, even in these sections, the bottom near the outer limit of the zone of light pollution was heavily silted in places. On the whole it seems probable that not more than 60 square miles of the total of 101.5 (Table 100) included in the three sections were formerly suitable for spawning.

Moreover, not all of the 60 square miles can be considered unsuitable now. In the River Raisin and Detroit River Sections certain stations arbitrarily enclosed by the outer limit of the zone of light pollution showed no evidence of pollution. The area of firm, clean bottom within this zone in the two sections probably was not less than 15 square miles. According to these estimates the total area rendered unfit for spawning, by pollution, was not more than 45 square miles, or 3.4 per cent of the water area of Western Lake Erie. The total area of Western Lake Erie formerly available for spawning is not known exactly, so it is not possible to determine what proportion has been made unavailable to the fish. In view of the large area of firm bottom in the island Section, it seems unlikely that the removal of 45 square miles at the west end would cause a serious scarcity of grounds for spawning.

It may be argued that pollution in Detroit River prevents the whitefish from migrating to Lake St. Clair, so that the area of spawning ground made unavailable is much greater than 45 square miles. This seems improbable, for the chemical evidence indicates that pollution in the river in mid-stream is not a barrier to migration.

The evidence, then, points toward the conclusion that pollution of the spawning grounds or their unavailability for others reasons, has not been the controlling factor in the depletion of the whitefish. The evidence applies with equal force to the cisco. Van Oosten (1930) showed that this species was depleted by intensive fishing when it was concentrated in a small area. The whitefish and cisco supply has been reduced to a greater extent than that of other commercial species in Lake Erie. Those species which commonly enter streams such as Maumee River and Raisin River to spawn may have had their spawning grounds reduced to a point which limits the production of young. However, many of these fishes, for example, the yellow pike-perch, will spawn in lakes if prevented from entering streams (Adams and Hankinson, 1928, page 442), and it is quite possible that they have suffered little from the interference with their normal spawning migration.

On the whole, pollution of the bottom in Western Lake Erie and in some of its tributaries must be considered as undesirable, and very likely has been positively harmful, but it seems highly improbable that it has been the primary factor in depletion of the fishery.

The plankton

In the preceding sections only the undesirable or harmful effects of pollution have been considered. There is little doubt that pollution has had at least one helpful effect, namely, that of increasing the abundance of plankton organisms, which serve as food for all young fishes and the adults of certain species.

It was found that there were marked differences in the abundance of phytoplankton in different sections of the area studied. The sections, listed in descending order with respect to abundance, were: (1) Maumee Bay, (2) River Raisin, (3) Portage River, (4) Island, (5) Detroit River. This is precisely the same order in which the sections arrange themselves with respect to intensity of pollution as indicated by the content of albuminoid ammonia. It is quite likely that the sections now relatively rich in plankton were also relatively rich under natural conditions. Yet there is little doubt that the algae of the plankton have increased to an important degree as the result of the additional nutritive material derived from domestic sewage.

The algae of the plankton perhaps are used very little as food for fishes, directly, but indirectly, they are important as food for crustacea and rotifers. The relative positions of the sections with respect to the abundance of crustacea of the plankton was the same as with respect to the abundance of phytoplankton. It is almost certain that the increase of phytoplankton (and of particulate, non-living, organic matter derived from sewage) has made possible an increase in the abundance of crustacea.

This increase in crustacea may be regarded as advantageous to the fishery, for it should permit more young fish to find an adequate supply of food, and thus to escape one of the hazards of post-larval life. Also it should permit the lake to maintain a larger population of adult individuals of plankton-feeding species. The advantage is not entirely restricted to the fishes which depend directly upon the plankton. Many bottom invertebrates subsist largely on detritus derived from dead plankton organisms, and it is reasonable to suppose that they have increased as a result of the additional food available to them. This increase should be passed along to the fishes of bottom-feeding habit. Briefly, the trophic standard of the lake has been raised by pollution, and the ability of the lake (from a nutritional point of view) to support fishes has been enhanced correspondingly.

Conclusion

As stated before, it is not possible to evaluate the harmful and helpful effects of pollution in numerical terms, to determine the total or residual effect on the fishery. Whether the residual effect of pollution has been to increase or decrease the productive capacity of the lake is open to question. Clearly pollution has not been an unmixed evil, and there is some basis for the view that it has done more good than harm. Even though the residual effect may have been detrimental, it seems highly improbable that pollution in the western part of the lake has been the primary or controlling factor in the depletion of the fishery of Lake Erie.

Bibliography

Adams, Charles C. and T. L. Hankinson.
1928. The ecology and economics of Oneida Lake fish. Roosevelt Wild Life Annals, Vol. I, No. 3 and 4, 1928, pp.235-548. Syracuse.

Adamstone, Frank B.
1924. The distribution and economic importance of the bottom fauna of Lake Nipigon with an appendix on the bottom fauna of Lake Ontario. University of Toronto Studies, Biological Series No. 25, Publications, Ontario Fisheries Research Laboratory, No. 24, 1924, pp. 34-100, 4 pl. Toronto.

Agassiz, Louis.
1850. Lake Superior: Its physical character, vegetation and animals compared with those of other and similar regions. Gould, Kendall, and Lincoln, Boston, 1850, xii + 428 pp.

Ahlstrom, Elbert H.
1930. Mollusks collected in Bass Island region, Lake Erie. The Nautilus, Vol. XLIV, No. 2, 1930, pp. 44-48. Boston.

1933. A quantitative study of Rotatoria in Terwilliger's Pond, Put-in-Bay, Ohio. The Ohio State University Bulletin, Vol. 38, No. 5, 1933, pp. 1-36. Columbus.

Allen, Winfred E.
1921. A brief study of range of error in micro-enumeration. Transactions, American Microscopical Society, Vol. XL, No. 1, 1921, pp. 14-25. Menasha.

American Public Health Association.
1925. Standard methods for the examination of water and sewage. Sixth edition, 1925, xi + 119 pp. New York.

Apstein, Carl.
1896. Das Süsswasserplankton. Methode und Resultate der quantitativan Untersuchung. Kiel und Leipzig, 1896, 200 S.

Bailey, L. W. and A. H. Mackay.
1921. The diatoms of Canada. Contributions to Canadian Biology, 1918-1920 (1921), pp. 115-124. Ottawa.

Bajkov, Alexander.

1929. Reports of the Jasper Park lakes investigations, 1925-26. VII. A study of the plankton. Contributions to Canadian Biology and Fisheries, being studies from the Biological Stations of Canada, New Series, Vol. IV, No. 24, 1929, pp. 345-396. Toronto.

Baker, Frank Collins.

1916. The relation of mollusks to fish in Oneida Lake. Technical Publication No. 4, The New York State College of Forestry, Vol. XVI, No. 21, 1916, 366 pp. Syracuse.

1918. The productivity of invertebrate fish food on the bottom of Oneida Lake, with special reference to mollusks. Technical Publication No. 9, The New York State College of Forestry, Vol. XVIII, No. 2, 1918, 264 pp. Syracuse.

1920. The life of the Pleistocene or Glacial Period. University of Illinois Bulletin, Vol. XVII, No. 41, 1920, xiv + 476 pp., 62 pl. Urbana.

1924. The fauna of the Lake Winnebago region. A quantitative and qualitative survey with special reference to the Mollusca. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XXI, 1924, pp. 109-146. Madison.

1928. The fresh water Mollusca of Wisconsin. Part I. Gastropoda. Part II. Pelecypoda. Bulletin, Wisconsin Geological Survey, No. 70, 1928, Part I, xx + 507 pp. Part II, vi + 495 pp. Madison.

1933. Studies on the bottom fauna of fresh-water lakes. Science, Vol. 78, No. 2018, September 1, 1933, pp. 190-191. Lancaster, Pa.

Barnard, H. E. and J. H. Brewster.

1909. The character of the water supply of Michigan City, Indiana. First Report, Lake Michigan Water Commission, 1909, pp. 135-189. Urbana.

Bartow, Edward.

1909. Report on water conditions in Illinois. First Report, Lake Michigan Water Commission, 1909, pp. 41-62. Urbana.

1909a. Methods of water analysis. First Report, Lake Michigan Water Commission, 1909, pp. 96-108. Urbana.

Bartow, Edward and Lewis I. Birdsall.
1911. Composition and treatment of Lake Michigan water. Second Report, Lake Michigan Water Commission, 1911, pp. 69-86. Urbana.

Baskina, V.
1926. Über die Giftwirkung des Phenols auf Cyclops insignis. Bulletin de l'Institut des recherches biologiques et de la Station Biologique á L'Université de Perm, Tome IV, Livraison 8, 1926, pp. 373-381. Perm.

Bayersdoerfer, Fritz.
1924. Beitráge zur Frage der Horizontalverbreitung des Zooplanktons in Bodensee. Internationale Revue der gesamten Hydrobiolgie und Hydrographie, Band XII, Heft 1-2 , 1924, S. 60-89. Leipzig.

Bigelow, N. K.
1922. Representative Cladocera of southwestern Ontario. University of Toronto Studies, Biological Series No. 20, Publications of the Ontario Fisheries Research Laboratory, No. 8, 1922, pp. 109-125, 4 pl. Toronto.

Birge, Edward A.
1881. Notes on crustacea in the Chicago water supply, with a note on the formation of the carapace. Medical Journal and Examiner, Vol. 14, 1881, pp. 584-590. Chicago.

1894. A report on a collection of Cladocera, mostly from Lake St. Clair, Michigan, with a table of species. Appendix II, Bulletin, Michigan Fish Commission, No. 4, 1894, pp. 45-47, Lansing.

1898. Plankton Studies on Lake Mendota. II. The Crustacea of the plankton from July, 1894, to December, 1896. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XI, 1896-1897 (1898), pp. 274-448. Madison.

1922. A second report on limnological apparatus. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XX, 1922, pp. 533-552. Madison.

Birge, Edward A. and Chancey Juday.
1911. The inland lakes of Wisconsin. The dissolved gases and their biological significance. Wisconsin Geological and Natural History Survey, Bulletin XXII, Scientific Series No. 7, 1911, xx + 259 pp. Madison.

Birge, Edward A. and Chancey Juday.

1920. A limnological reconnaissance of West Okoboji. University of Iowa Studies in Natural History, Vol. IX, No. 1, 1920, 56 pp. Iowa City.

1921. Further limnological observations on the Finger Lakes of New York. Bulletin, United States Bureau of Fisheries, Vol. XXXVII, 1919-1920 (1921), pp. 210-252. Washington.

1922. The inland lakes of Wisconsin. The plankton. I. Its quantity and chemical composition. Wisconsin Geological and Natural History Survey, Bulletin No. 64, Scientific Series No. 13, 1922, ix + 222 pp. Madison.

1926. Organic content of lake water. Bulletin, U. S. Bureau of Fisheries, Vol XLII, 1926, pp. 185-205. Washington.

1927. The organic content of the water of small lakes. Proceedings, American Philosophical Society, Vol. LXVI, 1927, pp. 354-372. Philadelphia.

Bormann, W. R.

1912. Seiches in lower Lake Michigan in May, 1912. Monthly Weather Review, Vol. 40, No. 9, 1912, pp. 1334-1335, 1 pl. Washington.

Briggs, S. A.

1872. The Diatomaceae of Lake Michigan. The Lens, Vol. I, 1872, pp. 41-44. Chicago.

Burkholder, Paul R.

1929. Biological significance of the chemical studies. In: Preliminary report on the cooperative survey of Lake Erie, season of 1928. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 65-72. Buffalo.

1929a. Microplankton studies of Lake Erie. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 73-93. Buffalo.

1930. A biological survey of Lake Erie. Science, New Series, Vol. 71, No. 1837, 1930, pp. 288-289. New York.

Burkholder, Paul R. and Willis L. Tressler.

1932. Plankton studies in some northern New York lakes. In: A biological survey of the Oswegatchie and Black River systems. State of New York Conservation Department, Supplemental to Twenty-first Annual Report, 1931 (1932), pp. 222-251. New York.

Campbell, Douglass H.
1886. Plants of the Detroit River. Bulletin, Torrey Botanical Club, Vol. XIII, No. 6, 1886, pp. 93-94 . New York.

Chicago Sanitary District, Engineering Board of Review.
1925. Report of the Engineering Board of Review of the Sanitary District of Chicago on the lake lowering controversy and a program of remedial measures. Part II. The Technical bases for the recommendations of the board of review. 1925, ix + 109 pp. Chicago.

1925a. Report of the Engineering Board of Review of the Sanitary District of Chicago on the lake lowering controversy and a program of remedial measures. Part III, Appendix I. Sewage disposal (An appendix to accompany Chapter IV of Part II), 1925, xix + 254 pp. Chicago.

Clark, H. Walton and C. B. Wilson.
1912. The mussel fauna of the Maumee River. Report, U. S. Commissioner of Fisheries for 1911 (1912), Bureau of Fisheries Document No. 757, 72 pp. Washington.

Clark, Levi J.
1892-1893. Lake currents. Transactions, Canadian Institute, Vol. 2, 1890-1891 (1892), pp. 154-157; ibid, Vol. 3, 1891-1892 (1893), pp. 275-280. Toronto.

Clarke, Frank W.
1924. The composition of the river and lake waters of the United States. United States Geological Survey, Professional Paper 135, 1924, iv + 199 pp. Washington.

Clemens, Wilbert A.
1915. Rearing experiments and ecology of Georgian Bay Ephemeridae. Contributions to Canadian Biology, being studies from the Biological Stations of Canada, 1911-1914, Fasciculus II, 1915, pp. 113-128, 3 pl. Ottawa.

1922. Hydra in Lake Erie. Science, New Series, Vol. 55, No. 1426, 1922, pp. 445-446. New York.

Clemens, Wilbert A., and N. K. Bigelow.
1922. The Food of Ciscoes (Leucichthys) in Lake Erie. Contributions to Canadian Biology, 1921 (1922), No. V, pp. 89-101. Toronto.

Cole, Leon J.
1905. The German carp in the United States. Appendix to the Report of the Commissioner of Fisheries to the Secretary of Commerce and Labor for the year ending June 30, 1904 (1905), pp. 523-641. Washington.

Coleman, Arthur P.

1922. Glacial and post-glacial lakes in Ontario. University of Toronto Studies, Biological Series, No. 21: Publications of the Ontario Fisheries Research Laboratory, No. 10, 1922, 76 pp. Toronto.

Comstock, C. B.

1872. Tides at Milwaukee, Wisconsin. In: Annual Report of the Chief of Engineers to the Secretary of War for the year 1872, Appendix Z (A), pp. 1035-1040, 6 pl. Washington.

1872a. Irregular oscillations in surface of Lake Michigan, at Milwaukee. In: Annual Report of the Chief of Engineers to the Secretary of War for the year 1872, Appendix Z (B), pp. 1040-1042. Washington.

1873. Water level and meteorological observations. Ibid. for the year 1873, Appendix BB, pp. 1172-1173, 1194, 2 pl. Washington.

Cooley, Lyman E.

1913. The Diversion of the waters of the Great Lakes by way of the sanitary and ship canal of Chicago. A brief of the facts and issues. The Sanitary District of Chicago, 1913; viii + 216 pp. Chicago.

Crohurst, H. R. and M. V. Veldee.

1927. Report of an investigation of the pollution of Lake Michigan in the vicinity of South Chicago and the Calumet and Indiana Harbors, 1924-1925. United States Public Health Service, Public Health Bulletin No. 170, 1927, vii and 134 pp. Washington.

Cutler, N. L.

1929. The biological investigations of pollution in the Erie-Niagara watershed. State of New York Conservation Department, Supplemental to the Eighteenth Annual Report, 1928 (1929), pp. 134-139. Albany.

Day, P. C.

1926. Precipitation in the drainage area of the Great Lakes, 1875-1924, with discussion of the levels of the separate lakes and their relation to the annual precipitation. Monthly Weather Review, Vol. 54, No. 3, 1926, pp. 85-101. Washington.

Deason, Hilary J.
1932. A study of the surface currents in Lake Michigan. The Fisherman, Vol. 1, No. 5, 1932, pp. 3-4 and 12. Grand Haven, Michigan.

Denison, F. Napier.
1897. The Great Lakes as a sensitive barometer. The Canadian Engineer, Vol. V., No. 6, 1897, pp. 158-161; No. 7, 1897, pp. 187-188. Toronto and Montreal.

Detroit Board of Health.
1902. Twenty-first annual report of the Board of Health of the City of Detroit, for the fiscal year ending June 30th, 1902. 84 pp. Detroit.

Detroit Department of Water Supply.
1930. The seventy-eighth annual report of the Board of Water Commissioners of the City of Detroit, for the year ending June 30, 1930, 80 pp. Detroit.

Dole, Richard B.
1909. The quality of surface waters in the United States. Part I. Analyses of waters east of the one hundredth meridian. United States Geological Survey, Water Supply Paper 236, 1909, 123 pp. Washington.

Domogalla, Bernhard P.
1926. Treatment of algae and weeds in lakes at Madison, Wisconsin. Engineering News-Record, Vol. 97, No. 24, 1926, pp. 950-954. New York.

Domogalla, Bernhard P., and E. B. Fred.
1926. Ammonia and nitrate studies of lakes near Madison, Wisconsin. Journal, American Society of Agronomy, Vol. 18, No. 10, 1926, pp. 897-911. Washington.

Domogalla, B.P., E. B. Fred, and W. H. Peterson.
1926. Seasonal variations in the ammonia and nitrate content of lake waters. Journal, American Water Works Association, Vol. 15, No. 4, 1926, pp. 369-385. Baltimore.

Domogalla, B. P., C. Juday, and W. H. Peterson.
1925. The forms of nitrogen found in certain lake waters. The Journal of Biological Chemistry, Vol. LXIII, No. 2, 1925, pp. 269-285. Baltimore.

Donaldson, Wellington and R. W. Furman.
1927. Quantitative studies of phenols in water supply. Journal, American Water Works Association, Vol. 18, No. 5, 1927, pp. 605-620. Baltimore.

Dymond, John R.
1926. The fishes of Lake Nipigon. University of Toronto Studies, Biological Series No. 27, Publications of the Ontario Fisheries Research Laboratory No. 27, 1926, pp. 1-108. Toronto.

Eddy, Samuel.
1927. The Plankton of Lake Michigan. Bulletin, Illinois Natural History Survey, Vol. XVII, Article IV, 1927, pp. 203-232. Urbana.

Eggleton, Frank E.
1931. A limnological study of the profundal bottom fauna of certain fresh-water lakes. Ecological Monographs, Vol. I, No. 3, 1931, pp. 231-332. Durham, North Carolina.

Ellms,, Joseph W.
1922. A sanitary survey of Lake Erie opposite Cleveland, Ohio, 1920. Journal, American Water Works Association, Vol. 9, No. 2, 1922, pp. 186-207. Baltimore.

1931. Water purification and sewage disposal on the Great Lakes. Scientific Monthly, Vol. XXXIII, No. 5, 1931, pp. 423-427. New York.

Endrös, Anton.
1908. Vergleichende Zusammenstellung der Hauptseichesperioden der bis jetzt untersuchten Seen mit Anwendung auf verwandte Probleme. Dr. A. Petermanns Mitteilungen aus Justus Perthes' Geographischer Anstalt, Band 54, Heft 2, pp. 39-47; Heft 3, S. 60-68; Heft 4, pp. 86-88. Gotha.

Ewers, Lela A.
1930. The Larval development of freshwater Copepoda. Contributions, The Franz Theodore Stone Laboratory of The Ohio State University, No. 3, 1930, 43 pp., 13 pl. Columbus.

1933. Summary report of crustacea used as food by the fishes of the western end of Lake Erie. Transactions, American Fisheries Society, Vol. 63, 1933, pp. 379-390. Washington.

Faigenbaum, Harold M.

1932. Chemical investigation of the Oswegatchie and Black River watersheds. State of New York Conservation Department, Biological Survey No. VI, Supplemental to 21st. Annual Report, 1931 (1932), pp. 150-188. New York.

Farrell, Michael A.

1932. Pollution studies. In: A biological survey of the Oswegatchie and Black River systems. State of New York, Conservation Department, Supplemental to Twenty-first Annual Report, 1931 (1932), pp. 189-198. New York.

Farwell, Oliver A.

1925. Botanical gleanings in Michigan. American Midland Naturalist, Vol. 9, No. 7, 1925, pp. 1-24. Notre Dame, Indiana.

Fell, George E.

1910. The currents at the easterly end of Lake Erie and head of Niagara River: their influence on the sanitation of the City of Buffalo, N. Y. Journal, American Medical Association, Vol. LV, No. 10, 1910, pp. 828-834. Chicago.

Ferrel, William.

1874. Tidal researches. Appendix, United States Coast Survey Report, 1874, 268 pp. Washington.

Fiedler, R. H.

1931. Fishery industries of the United States, 1929. Report, Commissioner of Fisheries for the fiscal year 1930 (1931), Appendix XIV, pp. 705-1068. Washington.

Fish, Charles J.

1929. Preliminary report on the cooperative survey of Lake Erie, season of 1928. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, 220 pp. Buffalo.

1929a. A preliminary report on the joint survey of Lake Erie. State of New York Conservation Department, Supplemental to Eighteenth Annual Report, 1928 (1929), pp. 39-106. Albany.

Follin, James W.

1916. Report on the investigation into the causes of the typhoid fever epidemic at Monroe, Michigan, occurring during the summer of 1915. Michigan State Board of Health, Engineering Bulletin No. 7, 1916, pp. 9-58, 11 maps, 9 figures. Lansing.

Forbes, Stephen A.

1882. On some Entomostraca of Lake Michigan and adjacent waters. American Naturalist, Vol. XVI, No. 7 and 8, 1882, pp. 537-542 and 640-649, 2 pl. Philadelphia.

1891. On some Lake Superior Entomostraca. Report, United States Commissioner of Fisheries, 1887 (1891), Bureau of Fisheries Document, No. 174, pp. 701-718, 4 pl. Washington.

Forbes, Stephen A., and R. E. Richardson.

1913. Studies on the biology of the upper Mississippi River. Bulletin, Illinois State Laboratory of Natural History, Vol. IX, Art. X, 1913, pp. 481-574. Urbana.

Foulk, Charles W.

1925. Industrial water supplies of Ohio, with chapters on impurities in water, methods of analysis and the statement of results and their interpretation, the behavior of water in use, and the industrial purification of water. Geological Survey of Ohio, Fourth Series, Bulletin No. 29, 1925, 406 pp. Columbus.

Fritsch, Felix E.

1931. Some aspects of the ecology of fresh-water algae (with special reference to static waters). Journal of Ecology, Vol. XIX, No. 2, 1931, pp. 233-272. Cambridge.

Frost, Wade H. et al.

1924. A study of the pollution and natural purification of the Ohio River. II. Report on surveys and laboratory studies. United States Public Health Service, Public Health Bulletin No. 143, 1924, xxi + 343 pp. Washington.

Fuller, Myron L.

1905. Failure of wells along the lower Huron River, Michigan, in 1904. Report, State Board of Geological Survey of Michigan for the year 1904 (1905), pp. 1-29. Lansing.

Gaillard, D. D.

1904. Wave action in relation to engineering structures. Professional Papers, Corps of Engineers, United States Army, No. 31, 1904, 232 pp. Washington.

Galtsoff, Paul S.

1924. Limnological investigations in the Upper Mississippi River, 1921. Bulletin, Bureau of Fisheries, Vol. XXXIX, 1923-1924 (1924), pp. 347-438. Washington.

Goodrich, Calvin, and Henry Vander Schalie.
1932. I. On an increase in the naiad fauna of Saginaw Bay, Michigan. II. The naiad species of the Great Lakes. Occasional Papers, Museum of Zoology, University of Michigan, No. 238, 1932, 14 pp. Ann Arbor.

Goodwin, W. L.
1892. The water supply of the City of Kingston, Ontario. Canadian Record of Science, Vol. 5, No. 2, 1892. pp. 117-127. Montreal.

Gottschall, Russell Y.
1930. Preliminary report on the phytoplankton and pollution in Presque Isle Bay, Lake Erie. Proceedings, Pennsylvania Academy of Science, Vol. 4, 1930, pp. 1-11. Philadelphia.

Graham, G. D.
1861. Investigation of the problem regarding the existence of a lunar tidal wave on the great freshwater lakes of North America. Proceedings, American Association for the Advancement of Science, 14th meeting, 1860 (1861), pp. 52-60. Cambridge.

Hankinson, Thomas L.
1916. Results of the Shiras Expeditions to Whitefish Point, Michigan: Fishes. Publications, Michigan Geological and Biological Survey, No. 20, Biological Series, No. 4, 1916, pp. 109-170. Lansing.

Harrington, Mark W.
1895. Surface currents of the Great Lakes, as deduced from the movements of bottle papers during the seasons of 1892, 1893 , and 1894. United States Department of Agriculture, Weather Bureau, Bulletin B (Revised edition), 1895, 14 pp., 6 pl. Washington.

Harris, Rollin A.
1902. Note on the oscillation period of Lake Erie. Monthly Weather Review, Vol. 30, No. 6, 1902, p.312. Washington.

1907. Tides in lakes and wells. In: Report, Superintendent of the Coast and Geodetic Survey, showing the progress of the work from July 1, 1906, to June 30, 1907, Appendix 6 (Manual of tides, Part V), 1907, pp. 463-486. Washington

Hayford, John F.
1922. Effects of winds and of barometric pressures on the Great Lakes. Carnegie Institution of Washington, Publication No. 317, 133 pp., 16 pl. Washington.

Henry, Alfred J.

1899. Sudden oscillations in lake level - pressure waves. Monthly Weather Review, Vol. 27, No. 7, 1899, pp. 305-307. Washington.

1902. Wind velocity and fluctuations of water level on Lake Erie. United States Department of Agriculture, Weather Bureau, Bulletin J, 1902, 22 pp., 13 pl. Washington.

Higgins, Elmer.

1928. Conference of Lake Erie biologists. Science, Vol. LXVII, No. 1734, 1928, pp. 309-310. New York.

1928a. Cooperative fishery investigations in Lake Erie, The Scientific Monthly, Vol. XXVII, 1928, pp. 301-306. New York.

1929. Can the Great Lakes fisheries be saved? Outdoor America, Vol. VII, No. 8, 1929. Chicago.

Hodgetts, William J.

1921-1922. A study of some of the factors controlling the periodicity of freshwater algae in nature. The New Phytologist, Vol. XX, No. 4, 1921, pp. 150-164; Vol. XX, No. 5, 1921, pp. 195-227; Vol. XXI, No. 1, 1922, pp. 15-33. London.

Horton, Robert E., and C. E. Grunsky.

1927. Hydrology of the Great Lakes. Report, Engineering Board of Review, Sanitary District of Chicago, on the lake lowering controversy and a program of remedial measures, Part III, Appendix II, 1927, xvii + 432 pp. Chicago.

Hough, J. L.

1935. The bottom deposits of southern Lake Michigan. Journal, Sedimentary Petrology, Vol. 5, Vol. 5, No. 2, pp. 57-80, 4 figs.

Hoy, Philo R.

1872. Deep-water fauna of Lake Michigan. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. I, 1870-1872 (1872), pp. 98-101. Madison.

Huntsman, Archibald G.

1915. The fresh-water Malacostraca of Ontario. Contributions to Canadian Biology, being studies from the Biological Stations of Canada, 1911-1914, Fasciculus II, 1915, pp. 145-163. Ottawa.

International Joint Commission (Canada and United States).

1914. Progress report in re the pollution of boundary waters, including report of the sanitary experts. Government Printing Office, January 16, 1914, 388 pp. Washington.

1918. Pollution of boundary waters. Report of the consulting sanitary engineer upon remedial measures. Government Printing Office, March 8, 1916 (1918), 159 pp. Washington.

1918a. Final report of the International Joint Commission in the matter of the reference by the United States and the Dominion of Canada relative to the pollution of boundary waters. Government Printing Office, 1918, 56 pp. Washington.

Jackson, Daniel D.

1912. Report on the sanitary condition of the Cleveland water supply, on the probable effect of the proposed changes in sewage disposal, and on the various sources of typhoid fever in Cleveland. 1912, 148 pp. Cleveland.

Jennings, Herbert S.

1900. A report of work on the protozoa of Lake Erie, with especial reference to the laws of their movements. Bulletin, United States Fish Commission for 1899, Vol. XIX, (1901), pp. 105-114. (Issued separately in 1900). Washington.

1903. Rotatoria of the United States. II. A monograph of the Rattulidae. Bulletin, United States Fish Commission for 1902 (1904), pp. 273-352, 15 pl. Washington. (Issued as separate in 1903).

Jennings, Otto E.

1930. Peregrinating Presque Isle. Carnegie Magazine, Vol. 4, No. 6, 1930, pp. 171-175. Pittsburgh.

1930a. A survey of the phytoplankton at Erie, Pennsylvania. Science, New Series, Vol. 71, No. 1848, 1930, pp. 560-561. New York.

Juday, Chancey.

1914. The inland lakes of Wisconsin. The hydrography and morphometry of the lakes. Wisconsin Geological and Natural History Survey, Bulletin XXVII, Scientific Series No. 9, 1914, xv + 137 pp. Madison.

1916. Limnological apparatus. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. 18, Part II, 1916, pp. 566-592. Madison.

Juday, Chancey.

1922. Limnological observations on Lake George. In: A biological survey of Lake George, New York, by James G. Needham, et al., State of New York Conservation Commission, 1922, 78 pp. Albany.

1924. Summary of quantitative investigations on Green Lake, Wisconsin. International Revue der gesanten Hydrobiologie und Hydrographie, Band XII, Heft 1-2, 1924, pp. 1-12. Leipzig.

1926. A third report on limnological apparatus. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XXII, 1926, pp. 299-314. Madison.

Juday, Chancey and E. A. Birge.

1932. Dissolved oxygen and oxygen consumed in the lake waters of northeastern Wisconsin. Transactions, Wisconsin Academy of Science, Arts, and Letters, Vol. XXVII, 1932, pp. 415-486. Madison.

Judson, W. V.

1909. Currents in Lake Michigan. First report of the Lake Michigan Water Commission, 1909, pp. 63-68. Urbana.

Kellicott, David S.

1878. Notes on the microscopic life in the Buffalo water supply. American Journal of Microscopy and Popular Science, Vol. III, No. 11, pp. 250-252. New York.

1879. The discovery of a new species of marine crustacea in the waters of Lake Erie. Reviewed in: Journal, Royal Microscopical Society, Vol. II, 1879, p. 152. London.

1896. The Rotifera of Sandusky Bay. Proceedings, American Microscopical Society, Vol. 18, 1896, pp. 155-164. Buffalo.

1897. The Rotifera of Sandusky Bay. Transactions, American Microscopical Society, Vol. 19, 1897, pp. 43-54. Buffalo.

Kellogg, Louise Phelps.

1917. Early narratives of the northwest, 1634-1699. Edited by Louise P. Kellogg. Charles Scribner's Sons, 1917, xiv + 382 pp. New York.

1925. The French Régime in Wisconsin and the Northwest. Wisconsin History Series, Vol. I, 1925, xv + 474 pp. Madison.

Kemmerer, George, J. F. Bovard, and W. R. Boorman.
1923. Northwestern lakes of the United States: Biological and chemical studies with reference to possibilities in production of fish. Bulletin, Bureau of Fisheries, Vol. XXXIX, 1923-1924 (1923), pp. 52-140. Washington.

Kennedy, Clarence H.
1922. The ecological relationships of the dragonflies of the Bass Islands of Lake Erie. Ecology, Vol. III, No. 4, 1922, pp. 325-336. Lancaster, Pennsylvania.

Kikuchi, Kenzo.
1930. Diurnal migration of plankton crustacea. Quarterly Review of Biology, Vol. 5, No. 2, 1930, pp. 189-206. Baltimore.

Kindle, Edward M.
1915. Limestone solution on the bottom of Lake Ontario. American Journal of Science, Fourth Series, Vol. 39, No. 234, 1915, pp. 651-656. New Haven.

1915a. Note on bottom currents in Lake Ontario. American Journal of Science, Fourth Series, Vol. XXXIX, 1915, pp. 192-196. New Haven.

1925. The bottom deposits of Lake Ontario. Transactions, Royal Society of Canada, third series, Vol. XIX, Part IV, 1925, pp. 47-102. Ottawa.

Klugh, A. Brooker.
1913. Notes on the algae of Georgian Bay. Rhodora, Vol. 15, No. 173, 1913, pp. 88-92. Boston and Providence.

1915. Notes on the aquatic plants of Georgian Bay. Contributions to Canadian Biology, being Studies from the Biological Stations of Canada, 1911-1914, Fasciculus II, 1915, pp. 219-220. Ottawa.

1927. The ecology, food-relations and culture of fresh-water Entomostraca. Transactions, Royal Canadian Institute, Vol. XVI, Part I, 1927, pp. 15-98. Toronto.

Koelz, Walter.
1926. Fishing industry of the Great Lakes. Report, United States Commissioner of Fisheries for 1925 (1926), Appendix XI, pp. 553-617. Washington.

Kofoid, Charles A.

1896. A report upon the protozoa observed in Lake Michigan and the inland lakes in the neighborhood of Charlevoix, during the summer of 1894. Appendix II to: A biological examination of Lake Michigan in the Traverse Bay region, by Henry B. Ward. Bulletin, Michigan Fish Commission, No. 6, 1896, pp. 76-84. Lansing.

1908. The Plankton of the Illinois River, 1894-1899. Part II. Constituent organisms and their seasonal distribution. Bulletin, Illinois State Laboratory of Natural History, Vol. VIII, Article I, 1908, 360 pp. Urbana.

Krecker, Frederick H.

1924. Conditions under which *Goniobasis livescens* occurs in the island region of Lake Erie. Ohio Journal of Science, Vol. XXIV, No. 6, 1924, pp. 299-310. Columbus.

1928. Periodic oscillations in Lake Erie. The Ohio State University, Franz Theodore Stone Laboratory, Contribution No. 1, 1928, 22 pp. Columbus.

1931. Verticle oscillations or seiches in lakes as a factor in the aquatic environment. Ecology, Vol. XII, No. 1, 1931, pp. 156-163. Lancaster, Pennsylvania.

Krecker, Frederick H. and L. Y. Lancaster.

1933. Bottom shore fauna of Western Lake Erie: a population study to a depth of six feet. Ecology, Vol. XIV, No. 2, 1933, pp. 79-93, Brooklyn.

Lachlan, R.

1855. On the periodical rise and fall of the lakes. American Journal of Science and Arts, Second Series, Vol. XIX, 1855, pp. 60-71, 164-175; Vol. 20, 1855, pp. 45-53, New Haven.

Landacre, F. L.

1908. The protozoa of Sandusky Bay and vicinity. Proceedings, Ohio Academy of Science, Vol. IV, Part 10, (Special Paper No. 13), 1908, pp. 423-472. Columbus.

Le Conte, John.

1884. Physical studies of Lake Tahoe, III. Rhythmic variations of level in lakes: or "seiches". Overland Monthly, Second Series, Vol. 3, No. 1, 1884, pp. 41-46. San Francisco.

Leighton, Marshall O.
1907. Pollution of Illinois and Mississippi Rivers by Chicago sewage. United States Geological Survey, Water Supply and Irrigation Paper No. 194, 1907, 369 pp. Washington.

Leverett, Frank.
1902. Glacial formations and drainage features of the Erie and Ohio basins. Monographs of the United States Geological Survey, Vol. XLI, 1902, 802 pp. Washington.

1929. Moraines and shore lines of the Lake Superior region. U.S. Geological Survey, Professional Paper 154-A, 1929, iv + 72 pp. Washington.

Leverett, Frank, and F. B. Taylor.
1915. The Pleistocene of Indiana and Michigan, and the history of the Great Lakes. Monographs of the United States Geological Survey, Vol. LIII, 1915, 529 pp. Washington.

MacClement, W. T.
1915. Preliminary report on the plants of Georgian Bay. A contribution to the biology of the Georgian Bay waters. Contributions to Canadian Biology, being Studies from the Biological Stations of Canada, 1911-1914, Fasciculus II, 1915, pp. 201-211. Ottawa.

Marsh, C. Dwight.
1895. Cyclopidae and Calanidae of Lake St. Clair, Lake Michigan, and certain of the inland lakes of Michigan. Bulletin, Michigan Fish Commission, No. 5, 1895, pp. 1-24, 9 pl. Lansing.

1903. The Plankton of Lake Winnebago and Green Lake. Bulletin, Wisconsin Geological and Natural History Survey, No. XII, 1903 , vi + 94 pp. Madison.

Martin, Lawrence.
1916. The physical geography of Wisconsin. Wisconsin Geological and Natural History Survey, Bulletin No. XXXVI, xxii + 549 pp. Madison.

Mason, William P.
1917. Examination of water, chemical and bacteriological. John Wiley and Sons, (Fifth Edition), 1917, vi + 194 pp. New York.

McDunnough, J.
1927. Notes on the species of the genus Hexagenia with description of a new species. Canadian Entomologist, Vol. 59, 1927, pp. 116-120. Orillia, Ontario.

McLaughlin, Allan J.

1911. Sewage pollution of interstate and international waters, with special reference to the spread of typhoid fever. I. Lake Erie and the Niagara River. United States Treasury Department, Hygienic Laboratory, Bulletin No. 77, 1911, 169 pp. Washington.

1912. Sewage pollution of interstate and international waters, with special reference to the spread of typhoid fever. II. Lake Superior and St. Marys River. III. Lake Michigan and the Straits of Mackinac. IV. Lake Huron, St. Clair River, Lake St. Clair, and the Detroit River. V. Lake Ontario and St. Lawrence River. United States Treasury Department, Hygienic Laboratory, Bulletin No. 83, 1912, 296 pp. Washington.

McNamee, Robert L.

1930. The surface waters of Michigan. Hydrology and qualitative characteristics and purification for public use. Bulletin, Department of Engineering Research, University of Michigan, No. 16, 1930, x + 318 pp. Ann Arbor.

Meehean, O. Lloyd.

1929. Manayunkia speciosa (Leidy) in the Duluth Harbor. Science, New Series, Vol. 70, No. 1820, 1929, pp. 479-480. New York.

Michigan Fisherman.

1928. Michigan Fisherman, Vol. XI, No. 5, 1928, p. 3, column 1. Bay City.

Miller, Ethel M.

1933. Bibliography of Ohio Botany, 1755-1931. The Ohio State University Bulletin, Vol. XXXVII, No. 5, 1932, pp. 283-376. (Ohio Biological Survey, Bulletin 27, Vol. 5, No. 4.) Columbus.

Miller, John A.

1929. The leeches of Ohio. The Ohio State University, Franz Theodore Stone Laboratory, Contribution No. 2 , 1929, 38 pp. Columbus.

Mills, Henry.

1882. Microscopic organisms in the Buffalo water-supply and in Niagara River. Proceedings, American Society of Microscopists, Fifth Annual Meeting, 1882, pp. 165-175. Buffalo.

Milner, James W.

1874. Report on the fisheries of the Great Lakes; the result of inquiries prosecuted in 1871 and 1872. Report, United States Commissioner of Fish and Fisheries for 1872 and 1873 (1874), Appendix A, pp. 1-78, Washington.

Moberg, Erik J.

1918. Variation in the horizontal distribution of plankton in Devils Lake, North Dakota. Transactions , American Microscopical Society, Vol. XXXVII, No. 4, 1918, pp. 239-267. Menasha.

Mohlmann, F. W. and C. C . Ruchhoft.

1927. The quality of Lake Michigan water, raw and treated, from Waukegan to Gary during 1926. Proceedings, Lake Michigan Sanitary Congress, Vol. III, No. 4, 1927, pp. 31-47. Chicago.

Moore, J. Percy.

1906. Hirudinea and Oligochasta collected in the Great Lakes region. Bulletin, United States Bureau of Fisheries, Vol. XXV, 1905 (1906), pp. 153-171. Washington.

Moseley, Edwin L.

1899. Sandusky flora: a catalogue of the flowering plants and ferns growing without cultivation, in Erie County, Ohio and the peninsula and islands of Ottawa County. Ohio Academy of Science, Special Papers, No. 1, 1899, pp. 1-167. Columbus.

1904. Formation of Sandusky Bay and Cedar Point. Proceedings, Ohio Academy of Science, Vol. IV, No. 5, 1904, pp. 179-238. Columbus.

1930. Fluctuation of bird life with change in water level. The Wilson Bulletin, Vol. XLII, No. 3, 1930, pp. 191-193. Sioux City, Iowa.

Muenscher, Walter C.

1929. Vegetation of Niagara River and the eastern end of Lake Erie. State of New York Conservation Department, Supplemental to Eighteenth Annual Report, 1928 (1929), pp. 189-197. Albany.

1932. Aquatic vegetation of the Oswegatchie and Black River watersheds (Including the eastern end of Lake Ontario and the upper stretch of the St. Lawrence River). State of New York Conservation Department, Supplemental to Eighteenth Annual Report, 1931 (1932), pp. 199-221. New York.

Muttkowski, Richard A.

1918. The fauna of Lake Mendota: a qualitative and quantitative survey with special reference to the insects. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XIX, Part I, 1918, pp. 374-482. Madison.

Nasmith, G. G. and F. Adams.

1914. Wind driven currents in the Great Lakes and their effect on municipal water supply. Journal of Preventive Medicine and Sociology, Vol. 16, No. 6, 1914, pp. 246-253. Toronto.

Naumann, Einar.

1918. Über die natürliche Nahrung des limnischen Zooplanktons. Ein Beitrag zur Kenntnis des Stoffhaushalts in Süsswasser. Lunds Universitets Årsskrift, Ny Foljd, Avd. 2, Bd. 14, Nr. 31, 1918, 47 S. Lund.

1932. Grundzüge der regionalen Limnologie. Die Binnengewässer, Band XI, 1932, xiv + 176 S. Stuttgart.

Neave, Ferris.

1932. A study of the May flies (*Hexagenia*) of Lake Winnipeg. Contributions to Canadian Biology and Fisheries, New Series, Vol. VII, No. 15, 1932, pp. 178-201. Toronto.

Newberry, J. S.

1874. Report on the geology of Erie County and the islands. Report, Geological Survey of Ohio, Vol. II, Part I, 1874, pp. 183-205. Columbus.

Nicholson, H. A.

1872. Preliminary report on dredgings in Lake Ontario. Annals and Magazine of Natural History, Fourth Series, Vol. 10, 1872, pp. 276-284. London.

Ohio State Board of Health.

1899. Second report of an investigation of the rivers of Ohio as sources of public water supplies. Thirteenth Annual Report, State Board of Health, State of Ohio, for the year ending October 31, 1898 (1899), Appendix I, pp. 328-491. Columbus.

1902. Fifth report of an investigation of the rivers of Ohio as sources of public water supplies. Sixteenth Annual Report, State Board of Health, State of Ohio, for the year ending October 31, 1901 (1902), Appendix I, pp. 325-427. Columbus.

Osborn, Herbert.
1930. Bibliography of Ohio zoology. Ohio Biological Survey, Vol. IV, No. 8 (Bulletin No. 23), 1930, pp. 353-410. Columbus.

Osburn, Raymond C.
1926. A preliminary study of the extent and distribution of sewage pollution in the west end of Lake Erie. Mimeographed report, 6 pp. Columbus.

1926a. Details regarding preliminary pollution survey of Lake Erie. Mimeographed report, 14 pp. Columbus.

Palmer, Arthur W.
1903. Chemical survey of the waters of Illinois. Report for the years 1897-1902. Published by the University of Illinois, 1903, 254 pp. Urbana.

Parmenter, Richard.
1929. Hydrography of Lake Erie. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 25-50. Buffalo.

Pearsall, W. H.
1922. A suggestion as to factors influencing the distribution of free-floating vegetation. Journal of Ecology, Vol. IX, No. 2, 1922, pp. 241-253. Cambridge.

1923. A theory of diatom periodicity. Journal of Ecology, Vol. XI, No. 2, 1923, pp. 165-183. Cambridge.

1932. Phytoplankton in the English lakes. II. The composition of the phytoplankton in relation to dissolved substances. Journal of Ecology, Vol. XX, No. 2, 1932, pp. 241-262. Cambridge.

Pearse, Arthur S.
1910. A preliminary list of the Crustacea of Michigan. Michigan Academy of Science, Twelfth Annual Report, 1910, pp. 68-76. Lansing.

Pearse, Arthur S. and H. Achtenberg.
1920. Habits of yellow perch in Wisconsin Lakes. Bulletin, Bureau of Fisheries, Vol. XXXWI, 1917-1918 (1920), pp. 297-366. Washington.

Pegrum, Reginald H.
1929. Topography of the Lake Erie Basin. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 17-24. Buffalo.

Perkins, E. A.
1893. The seiche in American Lakes. American Meteorological Journal, Vol. X, No. 6, 1893, pp. 251-263. Boston.

Peterson, W. H., E. B. Fred, and B. P. Domogalla.
1925. The occurrence of amino acids and other organic nitrogen compounds in lake water. Journal of Biological Chemistry, Vol. LXIII, No. 2, 1925, pp. 287-295. Baltimore.

Phelps, Earle B.
1917. Control of pollution of streams. The International Joint Commission and the pollution of boundary waters. U. S. Public Health Service, Public Health Reports, Vol. 32, No. 4, 1917, pp. 167-174. Washington.

Pieters, Adrian J.
1894. The plants of Lake St. Clair. Bulletin, Michigan Fish Commission, No. 2, 1894, 12 pp. Lansing.

1901. The plants of western Lake Erie, with observations on their distribution. Bulletin, United States Fish Commission for 1901, Vol. XXI, (1902), pp. 57-79. (Issued separately in 1901). Washington.

Plehn, M.
1924. Praktikum der Fischkrankheiten. E. Schweizerbart'sche Verlagsbuchhandlung, 179 S., 21 col. pl., 173 text fig. Stuttgart.

Pond, Raymond H.
1905. The biological relation of aquatic plants to the substratum. Report of the Commissioner of Fish and Fisheries for the year ending June 30, 1903 (1905), pp. 282-526. Washington.

Pritchard, Andrew L.
1931. Taxonomic and life history studies of the ciscoes of Lake Ontario. University of Toronto Studies, Biological Series No. 35: Publications, Ontario Fisheries Research Laboratory, No. 41, 1931, 78 pp. Toronto.

Rathbun, Richard and Wm. Wakeham.
1897. Report of the Joint Commission relative to the preservation of the fisheries in waters contiguous to Canada and the United States. House of Representatives, 54th Congress (Second session), Document No. 315, 1897, 178 pp. Washington.

Rawson, Donald S.
1930. The bottom fauna of Lake Simcoe and its role in the ecology of the lake. University of Toronto Studies, Biological Series No. 34, Publications of the Ontario Fisheries Research Laboratory, No. 40, 1930, 183 pp., 2 pl. Toronto.

Reed, H. S.
1899. An abnormal wave in Lake Erie. American Naturalist, Vol. XXXIII, No. 3 92 , 1899, pp. 653-660. Boston.

Reighard, Jacob E.
1893. Some plankton estimates in the Great Lakes. Transactions, American Fisheries Society, 1893, pp. 112-122. New York.

1894. A biological examination of Lake St. Clair. Bulletin, Michigan Fish Commission, No. 4, 1894, 60 pp., 1 pl. Lansing.

1894a. Some plankton studies in the Great Lakes. Bulletin, United States Fish Commission, Vol. XIII, 1893 (1894), pp. 127-142. Washington.

1897. Some characteristics of recent work on the biology of fresh waters. Proceedings, American Fisheries Society (26th Annual Meeting), 1897, pp. 41-46. Detroit.

1899. A plan for the investigation of the biology of the Great Lakes. Transactions, American Fisheries Society (28th Annual Meeting), 1899, pp. 65-76.

1899a. The biology of the Great Lakes. Science (New Series), Vol. IX, No. 235, 1899, pp. 906-907. New York.

Rice, Thurman.
1917. A study of the relations between plant growth and combined nitrogen in Winona Lake. Proceedings, Indiana Academy of Science, 1916 (1917), pp. 333-362. Fort Wayne.

Richardson, Robert E.
1928. The bottom fauna of the middle Illinois River, 1913-1925, its distribution, abundance, valuation, and index value in the study of stream pollution. Bulletin, Illinois Natural History Survey, Vol. XVII, Article XII, 1928, pp. 387-472, Urbana.

Riddle, Lumina C.
1902. Algae from Sandusky Bay. The Ohio Naturalist, Vol. III, No. 1, 1902, pp. 317-319. Columbus.

Ruthven, Alexander G. and others.

1911. A biological survey of the sand dune region on the south shore of Saginaw Bay, Michigan. Michigan Geological and Biological Survey, Publication 4, Biological Series 2, 1911, 347 pp. Lansing.

Sars, George O.

1915. Entomostraca of Georgian Bay. Contributions to Canadian Biology, being studies from the Biological Stations of Canada, 1911-1914, Fasciculus II, 1915, pp. 221-222. Ottawa.

Scott, Irving D.

1921. Inland Lakes of Michigan. Michigan Geological and Biological Survey, Publication No. 30, Geological Series 25, 1921, xxi + 383 pp. Lansing.

Scott, Will

1931. Investigations of Indiana Lakes. 3. The lakes of Northeastern Indiana. The Department of Conservation, State of Indiana, Publication No. 107, 1931, pp. 57-145. Indianapolis.

Scott, Will, Ralph Hile, and Herman T. Spieth.

1928. Investigations of Indiana lakes. 1. A quantitative study of the bottom fauna of Lake Wawasee (Turkey Lake). State of Indiana Department of Conservation, Division of Fish and Game, 1928, 25 pp. Indianapolis.

Shelford, Victor E.

1913. Animal communities in temperate America. University of Chicago Press, 1913, 362 pp. Chicago.

1917. An experimental study of the effects of gas waste upon fishes, with especial reference to stream pollution. Bulletin, Illinois State Laboratory of Natural History, Vol. XI, Article VI, 1917, pp. 380-412. Urbana.

Sherzer, William H.

1900. Geological report on Monroe County, Michigan. Geological Survey of Michigan, Vol. VII, Part I, 1900, xi + 240 pp. Lansing.

1913. Geological report on Wayne County. Michigan Geological and Biological Survey, Publication 12, Geological Series 9, 1913, 388 pp. Lansing.

Shuman, Jesse W.

1931. Notes on lake levels. Monthly Weather Review, Vol. 59, No. 3, 1931, pp. 97-105. Washington.

Sibley, C. K.
1932. Fish food studies. In: A biological survey of the Oswegatchie and Black River systems. State of New York Conservation Department, Supplemental to Twenty-first Annual Report, 1931 (1932), pp. 120-132. New York.

Smith, Gilbert M.
1924. Ecology of the plankton algae in the Palisades Interstate Park, including the relation of control methods to fish culture. Roosevelt Wild Life Bulletin, Vol. 2, No. 2, 1924, pp. 93-195. Syracuse.

Smith, Hugh M.
1898. Biological survey of Lake Erie. Science, New Series, Vol. VIII, No. 183, 1908, pp. 13-14. New York.

Smith, Sidney I.
1871. Preliminary report on the dredgings in Lake Superior. Report of the Secretary of War for 1871, Part 2, pp. 1-7. Washington.

1874. Sketch of the invertebrate fauna of Lake Superior. Report, Commissioner of Fish and Fisheries for 1872-1873 (1874), Appendix F, Article 27, pp. 609-707. Washington.

Snow, Julia W.
1903. The plankton algae of Lake Erie, with special reference to the Chlorophyceae. Bulletin, United States Fish Commission for 1902, Vol. XXII, (1904), pp. 369-394. (Issued separately in 1903). Washington.

Southern, R. and A. C. Gardiner.
1926. Reports from the Limnological Laboratory. I. The seasonal distribution of the crustacea of the plankton in Lough Derg and the River Shannon. Scientific Investigations, Ireland Department of Fisheries, 1926, No. I, 170 pp., 15 pl. Dublin.

Stehle, Mabel E.
1923. Surface plankton protozoa from Lake Erie in the Put-in-Bay region. Ohio Journal of Science, Vol. XXIII, No. 1, 1923, pp. 41-54. Columbus.

Steuer, Adolf.
1910. Planktonkunde. 1910, xv + 723, S. Leipzig und Berlin.

Stewart, Norman Hamilton.
1926. Development, growth, and food habits of the white sucker, Catostomus commersonii LeSeuer. Bulletin, Bureau of Fisheries, Vol. XLII, 1926, pp. 147-184. Washington.

Stimpson, William.
1870. On the deep-water fauna of Lake Michigan. American Naturalist, Vol. 4, No. 7, 1870, pp. 403-405. Salem.

Streeter, H. W.
1930. Studies of the efficiency of water purification processes. IV. Report on a collective survey of the efficiency of a selected group of municipal water purification plants located along the Great Lakes. United States Public Health Service, Public Health Bulletin No. 193, 1929 (1930), vi + 100 pp. Washington.

Thienemann, August.
1925. Die Binnengewässer Mitteleuropas. Eine limnologische Einführung. Die Binnengewässer, Band I, 1925, 255 S. Stuttgart.

Thomas, B. W. and H. H. Chase.
1886. Diatomaceae of Lake Michigan as collected during the last sixteen years from the water supply of the City of Chicago. Chicago, 1886. Also: Notarisia, Commentarium Phycologicum, Anno 2, N. 6, 1887, pp. 328-330. Venice.

Thompson, David H.
1925. Some observations on the oxygen requirements of fishes in the Illinois River. Bulletin, Illinois Natural History Survey, Vol. XV, Article VII, 1925, pp. 423-437. Urbana.

Thompson, H. D.
1896. Report on the plants. Appendix I to: A biological examination of Lake Michigan in the Traverse Bay region, by Henry B. Ward. Bulletin, Michigan Fish Commission, No. 6, 1896, pp. 72-75. Lansing.

Thwaites, Reuben Gold.
1898. The Jesuit Relations and Allied Documents. Edited by R. G. Thwaites, Vol. XXXIII, 1648-1649 (1898), 274 pp. The Burrows Brothers Co., Cleveland.

Tiffany, Lewis H.
1933. The plankton algae of the islands region of the west end of Lake Erie. Contributions, Franz Theodore Stone Laboratory (Ohio State University), No. 6, 1934, 112 pp., 15 pl., 1 map. Columbus.

Tiffany, Lewis H., and Elbert H. Ahlstrom.
1931. New and interesting plankton algae from Lake Erie. The Ohio Journal of Science, Vol. XXXI, No. 6, 1931, pp. 455-467. Columbus.

Transeau, Edgar N.
1916. The periodicity of freshwater algae. American Journal of Botany, Vol. III, No. 3, 1916, pp. 121-133. Lancaster, Pa.

Tressler, Willis L. and B. P. Domogalla.
1931. Limnological studies of Lake Wingra. Transactions, Wisconsin Academy of Sciences, Arts, and Letters, Vol. XXVI, 1931, pp. 331-351. Madison.

Turner, Clarence L.
1926. The crayfishes of Ohio. Ohio Biological Survey, Vol. III, No. 3 (Bulletin No. 13), 1926, pp. 145-195. Columbus.

United States Geological Survey
1925-1932. Surface water supply of the United States. Part IV. St. Lawrence River Basin. Water-supply Papers, United States Geological Survey, No. 544, 1922 (1925), 140 pp.; No. 564, 1923 (1926), 171 pp.; No. 584, 1924 (1927), 147 pp.; No. 604, 1925 (1929), 179 pp.; No. 624, 1926 (1930), 163 pp.; No. 644, 1927 (1930), 156 pp.; No. 664, 1928 (1931), 119 pp.; No. 684, 1929 (1931), 123 pp.; No. 699, 1930 (1932), 125 pp. Washington.

United States Lake Survey.
1931. Survey of northern and northwestern lakes. Bulletin, United States Lake Survey, No. 40, 1931, 472 pp. Detroit.

United States Tariff Commission.
1927. Lake fish. Tariff Information Series, No. 36, 1927, 175 pp. Washington.

Van Oosten, John.
1929. Life history of the lake herring (Leucichthys artedi Le Sueur) of Lake Huron as revealed by its scales, with a critique of the scale method. Bulletin, U. S. Bureau of Fisheries, Vol. XLIV, 1928 (1929), pp. 265-428. Washington.

1929a. Some fisheries problems on the Great Lakes. Transactions, American Fisheries Society, Vol. 59, 1929, pp. 63-85. Hartford.

1930. The disappearance of the Lake Erie cisco - a preliminary report. Transactions, American Fisheries Society, Vol. 60, 1930, pp. 204-214. Hartford.

Vorce, C. M.

1880. The minute forms of life in the waters of the lakes. American Journal of Microscopy and Popular Science, Vol. V, No. 12, 1880, pp. 263-265. New York.

1881. Forms observed in water of Lake Erie. Proceedings, American Society of Microscopists, 4th Annual Meeting, pp. 50-60, 1 pl. Buffalo.

1882. Microscopical forms observed in water of Lake Erie. Proceedings, American Society of Microscopists, 5th Annual Meeting, pp. 187-196, 1 pl. Buffalo.

Wagner, Frederick E.

1929. Chemical investigation of the Erie- Niagara watershed. State of New York Conservation Department, Supplemental to the 18th Annual Report, 1928 (1929), pp. 107-133. Albany.

Walton, Lee B.

1915. A review of the described species of the order Flagellata (Protozoa) with particular reference to those found in the city water supplies and in other localities of Ohio. Ohio Biological Survey, Vol. I, Bulletin 4, 1915. pp. 342-449. Columbus.

Ward, Henry B.

1895. The food supply of the Great Lakes; and some experiments on its amount and distribution. Proceedings, American Microscopical Society, Vol. XVII, 1895, pp. 242-254. Buffalo.

1896. A biological examination of Lake Michigan in the Traverse Bay region. Bulletin, Michigan Fish Commission, No. 6, 1896, 99 pp., 5 pl. Lansing.

Wasmund, Erich.

1927-
1928. Die Strömungen im Bodensee verglichen mit bisher in Binnenseen bekannten Strömen. Internationale Revue der gesamten Hydrobiologie und Hydrographie, Band XVIII, Heft 1-2, 1927, S. 84-114; Heft 3-4, 1927, S. 231-260; ibid. Band XIX, Heft 1-2, 1928, S. 21-155. Leipzig.

West, George S. and F. E. Fritsch.

1927. A treatise on the British freshwater algae, in which are included all the pigmented protophyta hitherto found in British freshwaters. University Press, 1927, xvii + 524 pp. Cambridge.

West, W. and G. S. West.

1912. On the periodicity of the phytoplankton of some British lakes. Journal, Linnean Society (Botany), Vol. 40, 1912, pp. 395-432. London.

Whipple, George C.

1894. Some observations on the growth of diatoms in surface waters. Technology Quarterly and Proceedings of the Society of Arts (Massachusetts Institute of Technology), Vol. VII, 1894, pp. 214-231. Boston.

1905. Report on the quality of the water supply of the city of Cleveland, Ohio. 1905. Cleveland.

1913. Effect of the sewage of Rochester, N. Y. on the Genesee River and Lake Ontario under present conditions. Appendix V, pp. 177-239, in: Report on the sewage disposal system of Rochester, N. Y., by E. A. Fisher, 1913, 248 pp. Rochester.

1927. The microscopy of drinking water. Fourth edition, revised by G. M. Fair and M. C. Whipple, 1927, xix + 586 pp., 19 pl. John Wiley and Sons, New York.

Whiting, Henry.

1831. Remarks on the supposed tides, and periodic rise and fall of the North American lakes. American Journal of Science and Arts, Vol. XX, 1831, pp. 205-219. New Haven.

Whittlesey, Charles.

1851. On the observed fluctuations in the surfaces of the lakes. In: Report on the geology of the Lake Superior land district. Part II. The iron region; by J. W. Foster and J. D. Whitney. U. S. Senate, Special Session, March, 1851, Executive No. 4, pp. 319-358. Washington.

1859. On the fluctuations of the water level at Green Bay, Wisconsin. American Journal of Science and Arts, Second Series, Vol. XXVII, 1859, pp. 305-310, 447. New Haven.

1875. Sudden fluctuations of level in quiet waters-records of observations. Proceedings, American Association for the Advancement of Science, Twenty-third Meeting. Hartford, Connecticut, August, 1874 (1875), pp. 139-143. Salem.

Wickliff, Edward L.

1920. Food of young small-mouth black bass in Lake Erie. Transactions, American Fisheries Society, 1920, pp. 364-371. Washington.

Wickliff, Edward L.
1931. Fishery research by the Ohio Division of Conservation. Transactions, American Fisheries Society, Vol. 61, 1931, pp. 199-207.

Wiebe, Abraham H.
1926. Variations in the freshwater snail, Goniobasis livescens. Ohio Journal of Science, Vol. XXVI, No. 2, March, 1926, pp. 49-68. Columbus.

1928. Biological survey of the upper Mississippi River, with special reference to pollution. Bulletin, Bureau of Fisheries, Vol. XLIII, Part II, 1927 (1928), pp. 137-167. Washington.

Williams, Roger C.
1929. Pollutional studies in the light of the chemical analyses. In: Preliminary report on the cooperative survey of Lake Erie, season of 1928. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 60-64. Buffalo.

Wilson, Charles B.
1929. The macroplankton of Lake Erie. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV , No. 3, 1929, pp. 94-135. Buffalo.

Wisconsin State Board of Health.
1927. Stream pollution in Wisconsin. Special report. A joint report of the Conservation Commission and State Board of Health of Wisconsin concerning activities in the control of stream pollution, from July 1, 1925 to December 31, 1926. (1927), xviii + 328 pp. Madison.

Wolf, Eugene.
1905. Die Fortpflanzungsverhältnisse unserer einheimischen Copepoden. Zoologische Jahrbücher, Abteilung für Systematik, Geographie und Biologie der Tiere, Band 22, 1905, S. 101-280. Jena.

Woltereck, Richard.
1932. Races, associations and stratification of pelagic daphnids in some lakes of Wisconsin and other regions of the United States and Canada. Transactions, Wisconsin Academy of Sciences, Arts and Letters, Vol. 27, 1932, pp. 487-522. Madison.

Wright, Stillman.
1931. Bottom temperatures in deep lakes. Science, New Series, Vol. 74, No. 1921, 1931, p. 413. New York.

Wright, Stillman and Wilbur Tidd.
1933. Summary of limnological investigations in Western Lake Erie in 1929 and 1930. Transactions, American Fisheries Society, Vol. 63, 1933, pp. 271-285, 2 figs. Washington.

Zillig, Andrew M.
1929. Bacteriological studies of Lake Erie. Bulletin, Buffalo Society of Natural Sciences, Vol. XIV, No. 3, 1929, pp. 51-57.

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